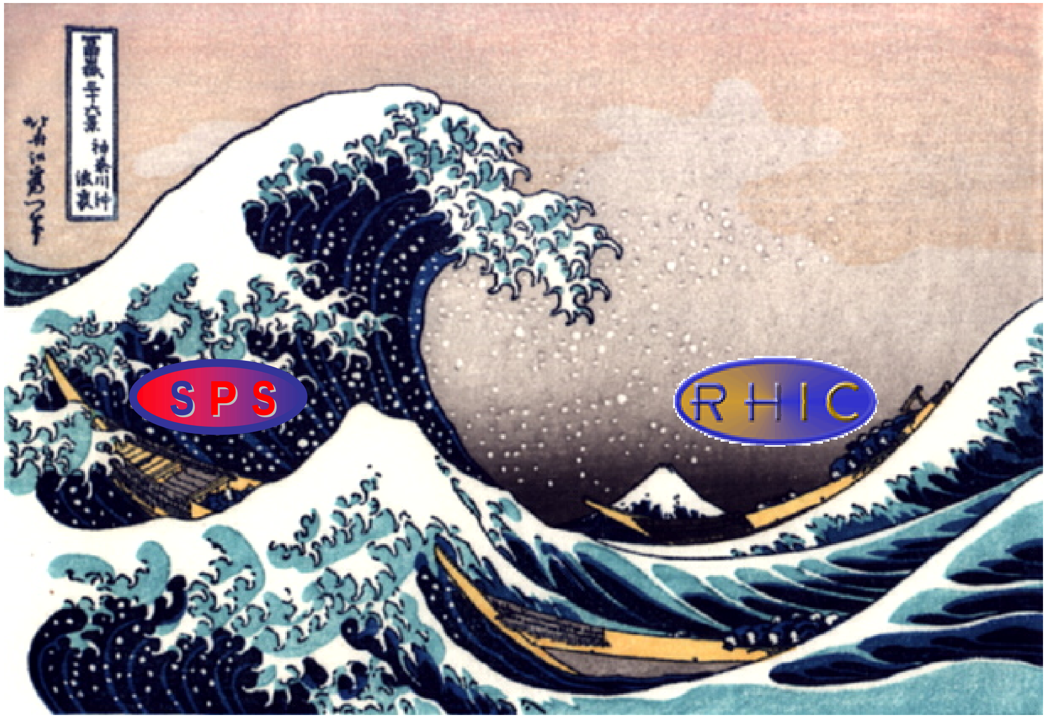
Probing properties of hadron production at RHIC: Hints of Thermalization and Collective Behaviour



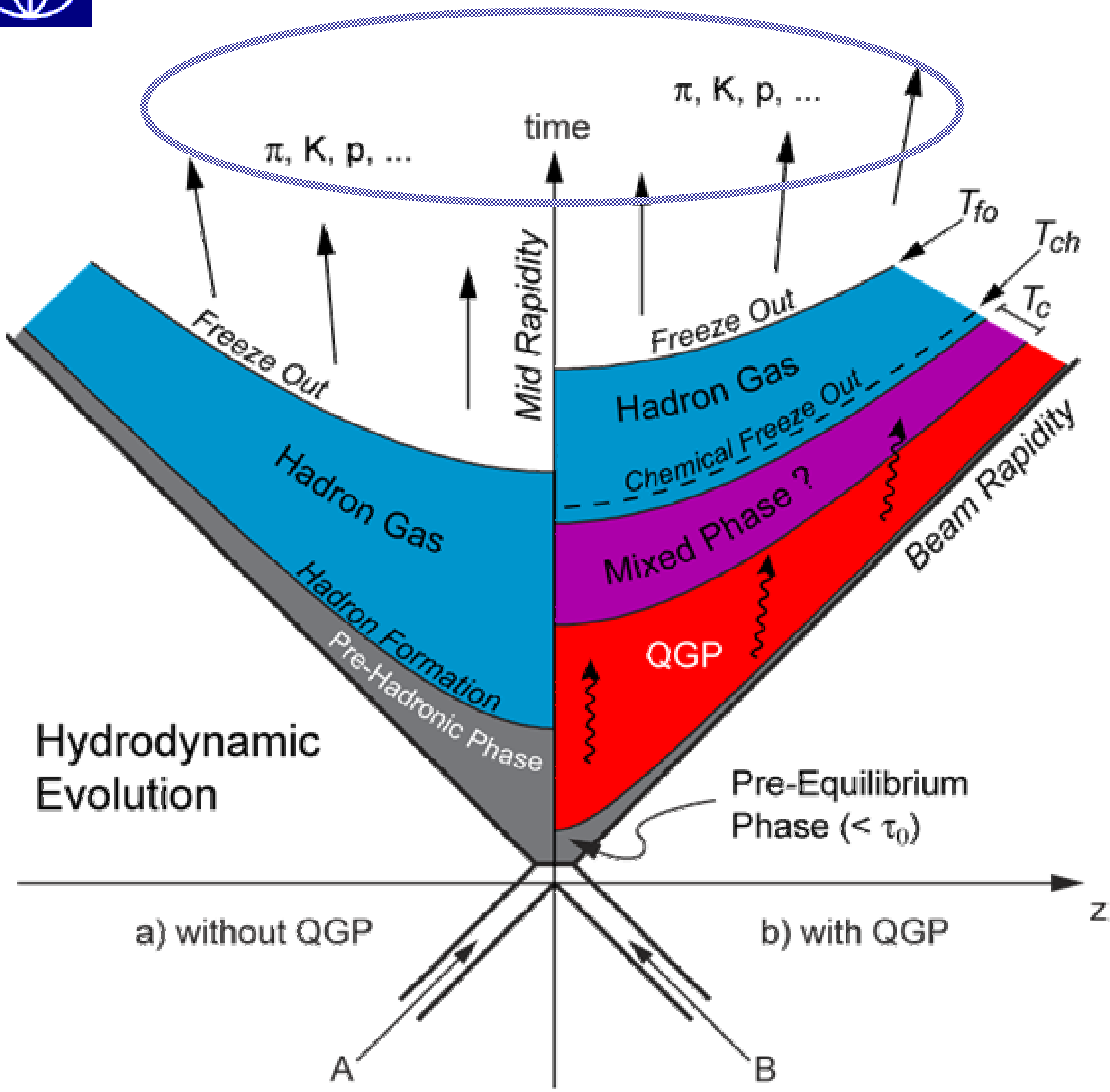
"The Great Wave of Kanagawa", Katsushika Hokusai (1760-1849).

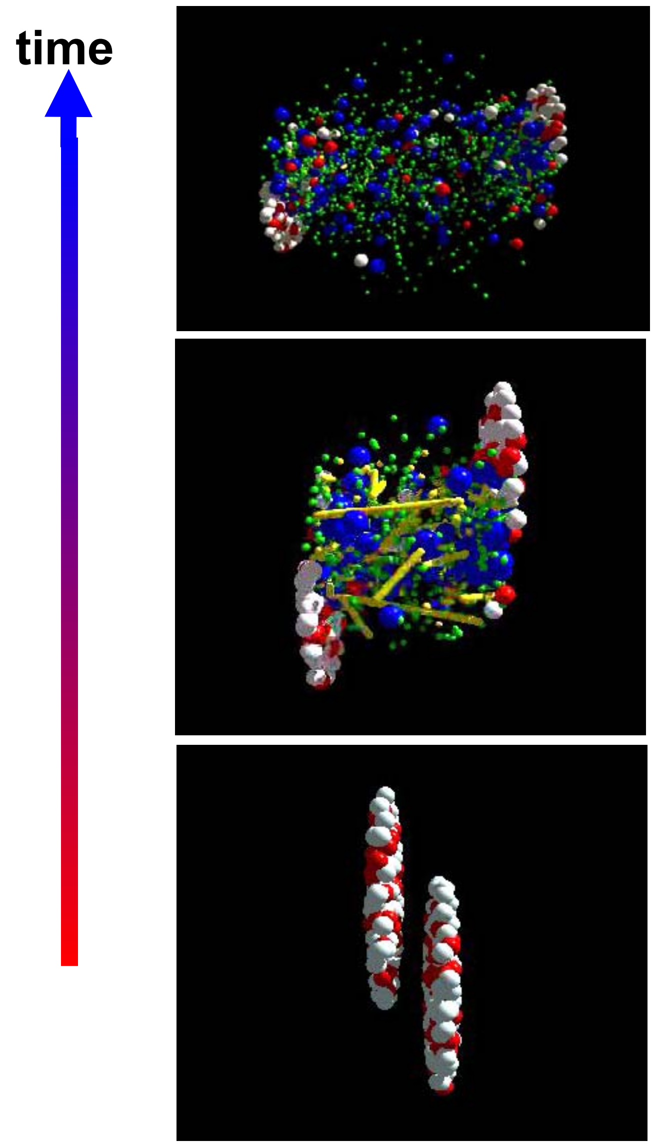
Outline

- Stages of Heavy ion collisions;
- Hydrodynamical description;
- Particle density at RHIC;
- Thermodynamical description;
- Strangeness and rescattering.

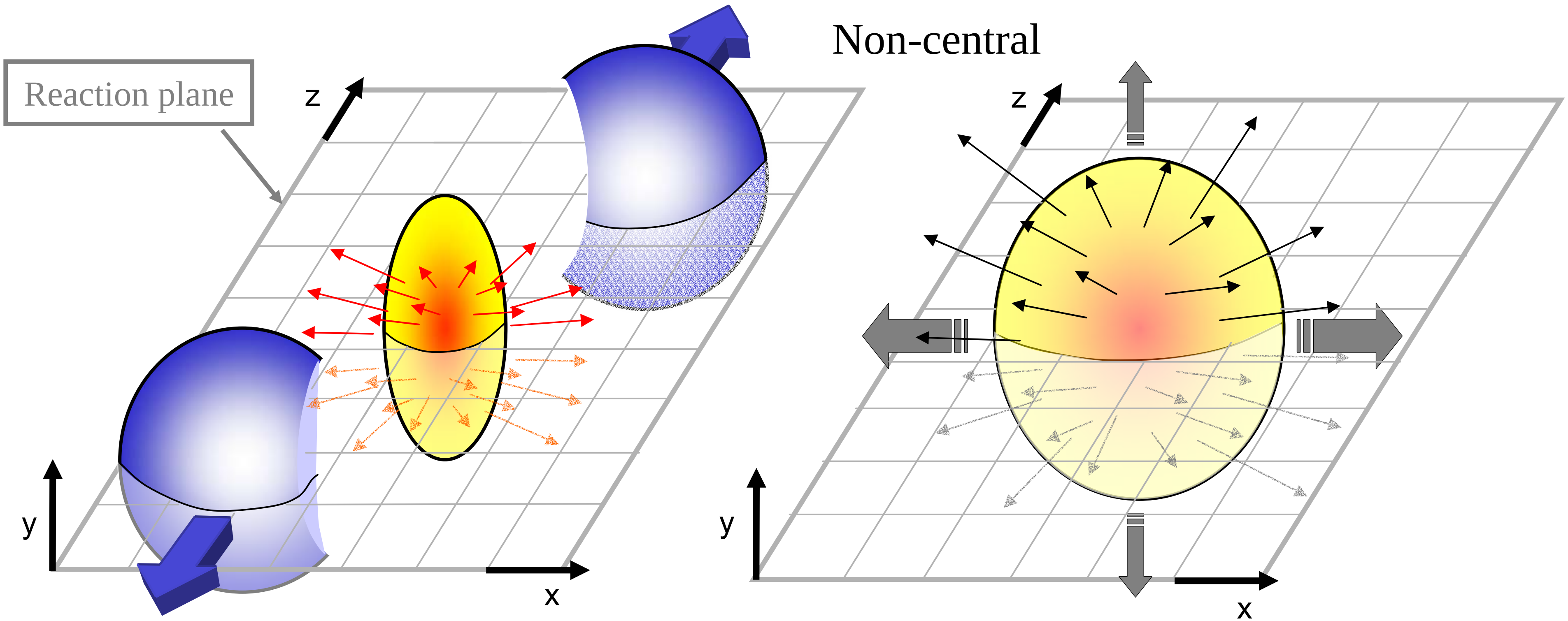
Boris Hippolyte (YALE), for the STAR Collaboration.

The Phase Transition in the Laboratory





Geometry of the Collision …

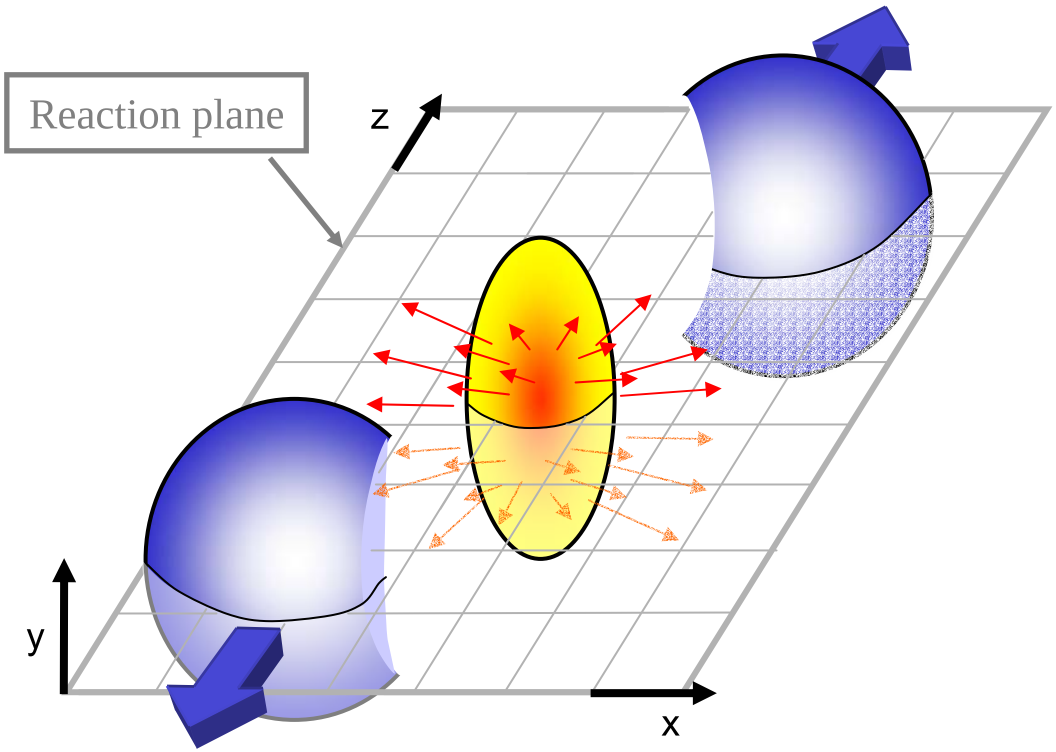


Number of participants (N_{part}): number of incoming nucleons in the overlap region
Number of binary collisions (N_{bin}): number of inelastic nucleon-nucleon collisions

Expansion of the fireball:
higher pressure gradient in the reaction plane
ellipsoidal ⇨ spherical

Elliptic Flow: the early stages of the collision …

Modeling the Ideal Liquid

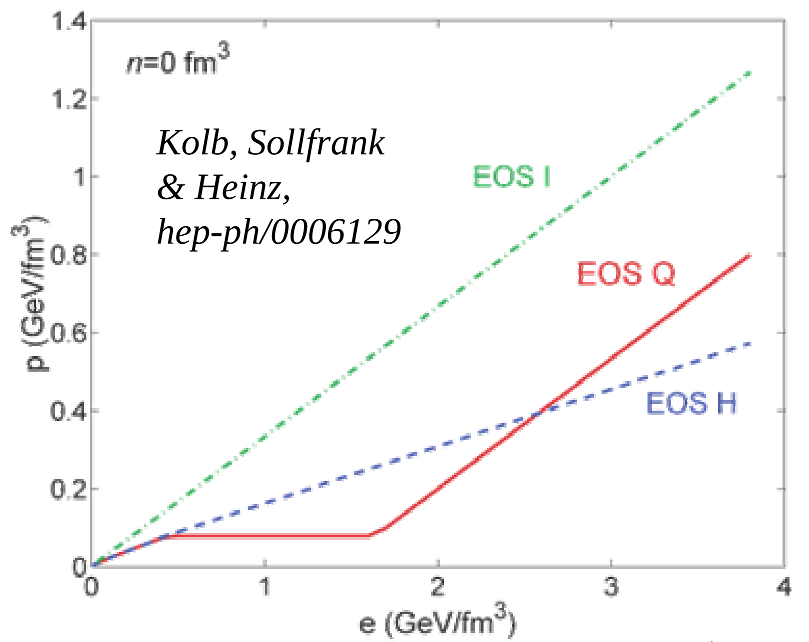


Direct access to underlying physics but initial conditions are needed as well as hadronization mechanism(s).

Assumes local thermal equilibrium (zero mean-free-path limit) and solves equations of motion for fluid elements ("constituents"… not particles!)

(i) Equations given by continuity, conservation laws.

(ii) Equation of state (EOS) which relates quantities (P,T,chemical potentials,V).



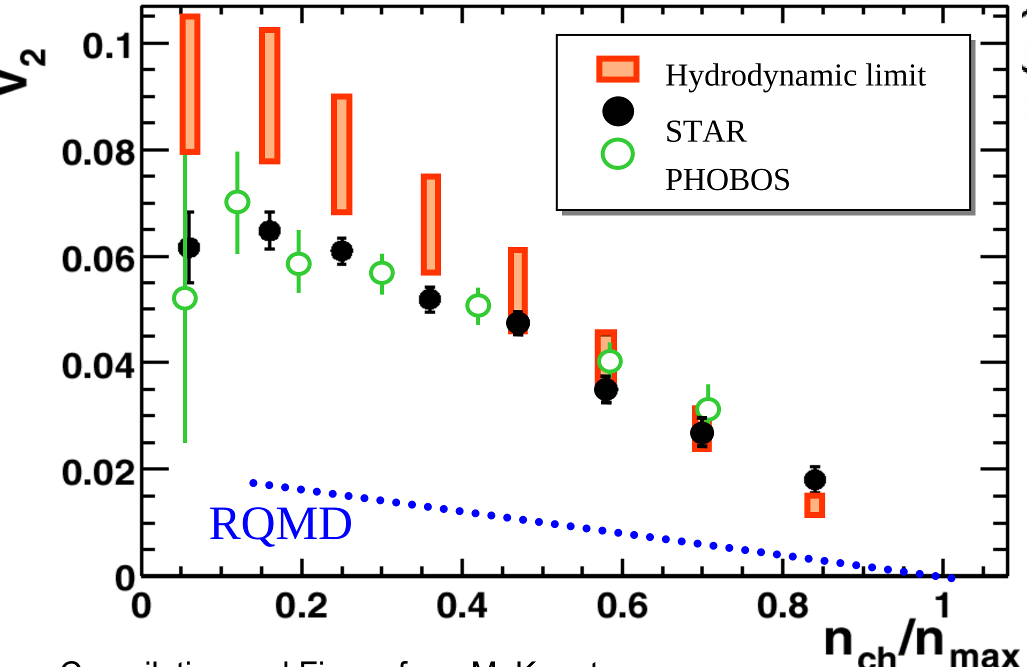
$$\frac{dN}{dYp_T dp_T d\varphi} = \frac{dN}{dYp_T dp_T}\frac{1}{2\pi}\left(1 + 2v_1\cos(\varphi) + 2v_2\cos(2\varphi) + 2v_4\cos(4\varphi) + \ldots\right)$$

Elliptic flow

$$v_2 = \langle \cos 2(\varphi - \Psi_r) \rangle$$

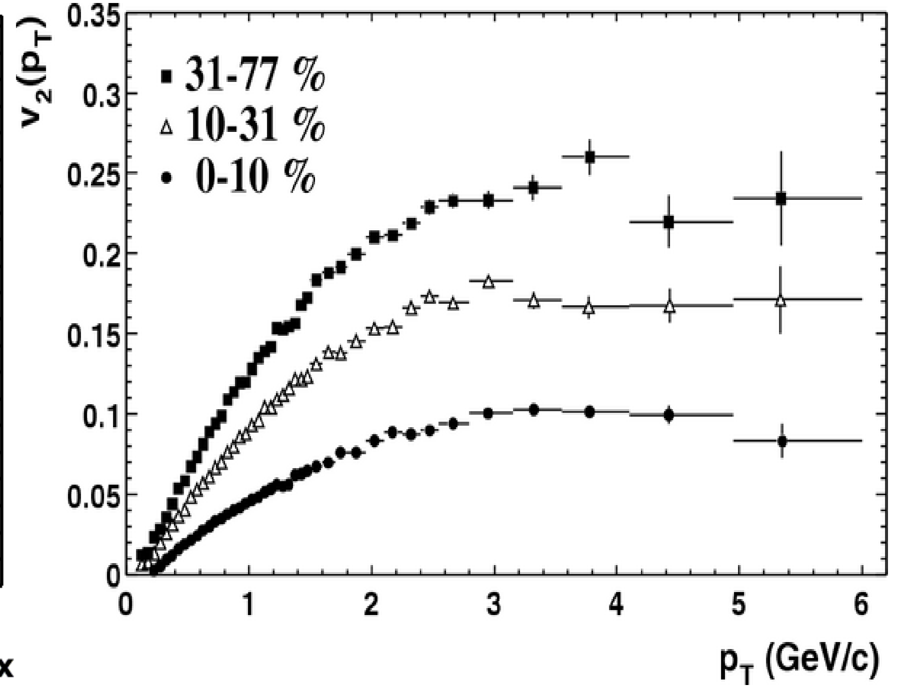
PHOBOS: Phys. Rev. Lett. **89**, 222301 (2002)

STAR: Phys. Rev. Lett. **86**, 402 (2001)



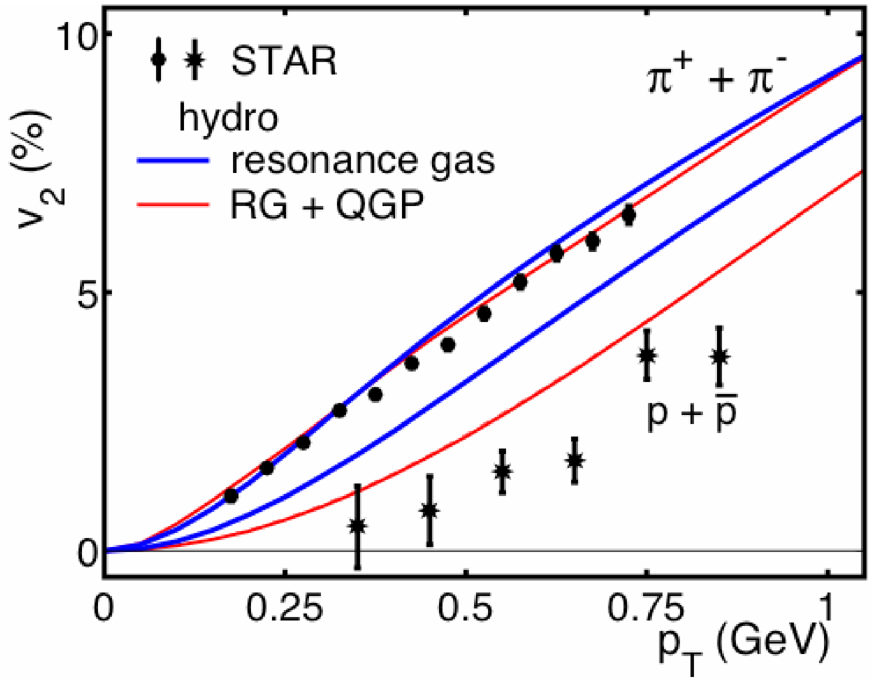
Compilation and Figure from M. Kaneta

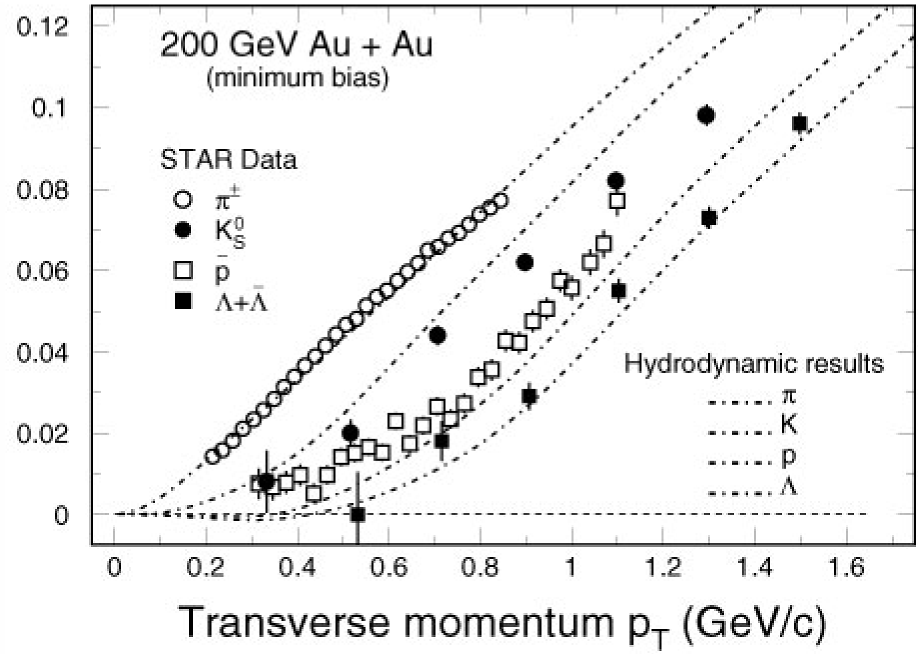
STAR: Phys. Rev. Lett. **90**, 032301 (2003)



First time in Heavy-Ion Collisions a system created which at low p_t is in quantitative agreement with ideal hydrodynamic model predictions for v_2 from most central to mid-central collisions

Identified Elliptic flow at low p_T

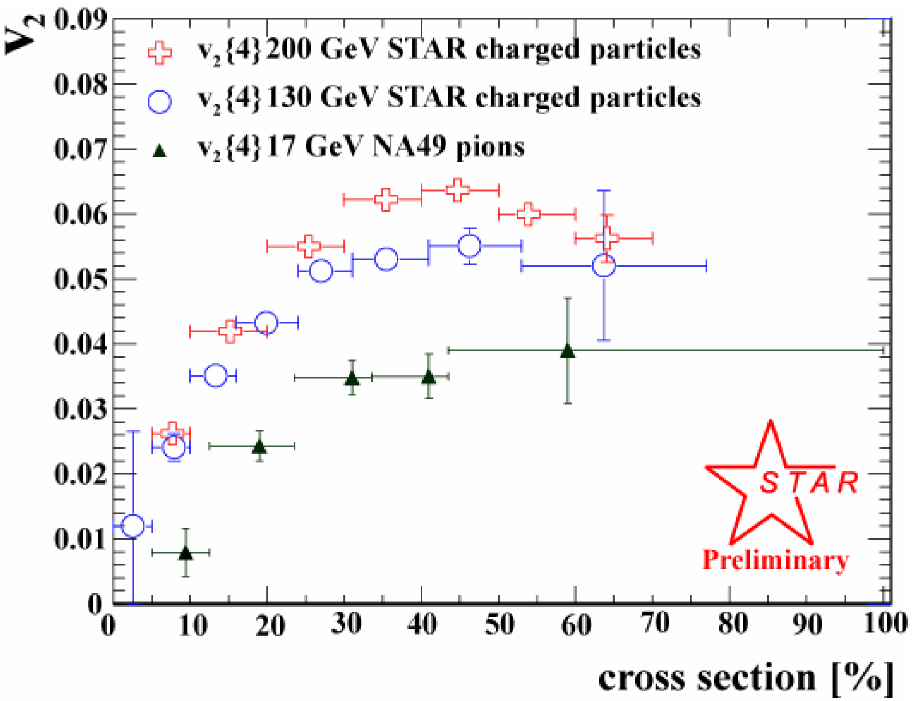




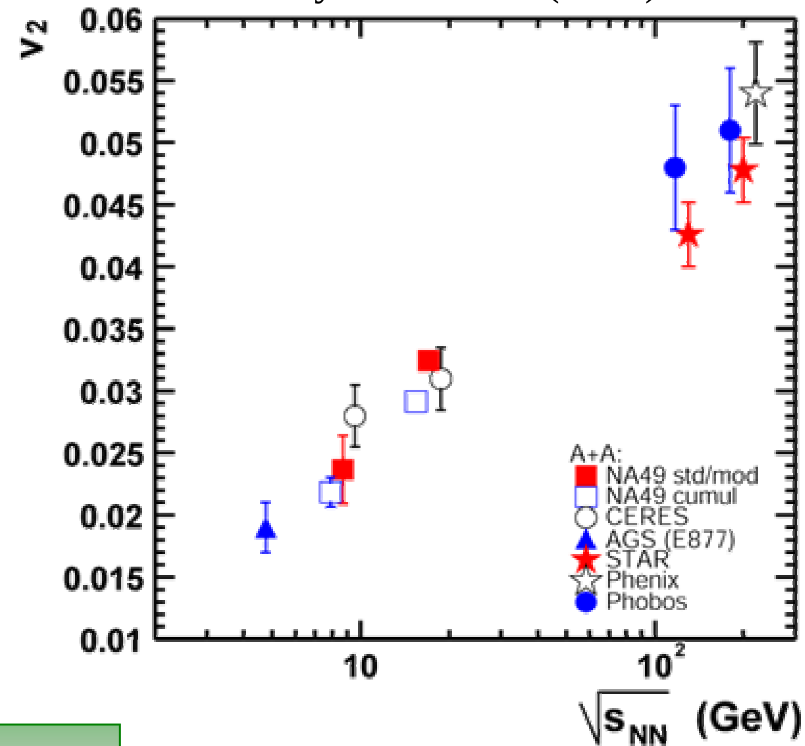
Hydro calculations: Kolb, Heinz and Huovinen

- Clear mass dependence; signature of collective flow (not only in hydro)
- Hydrodynamics gives reasonable description of various mass particles at low transverse momenta
- Hydro calculation constrained by particle spectra

Energy dependence of v_2



NA49 Phys.Rev. C 68 (2003) 034903

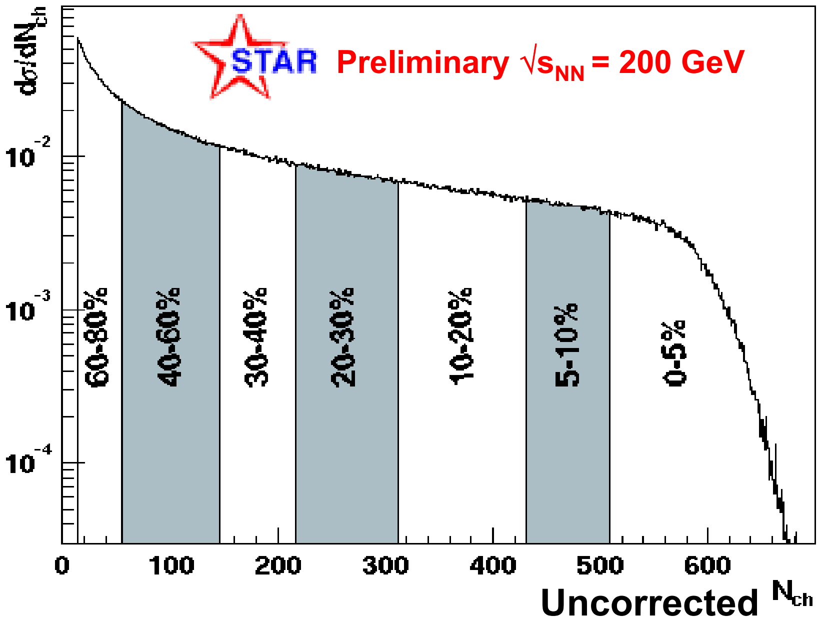


For predictions:

- P.F. Kolb and U. Heinz, nucl-th/0305084;
- Pasi Huovinen, nucl-th/0305064.
- D. Teaney, J. Lauret and E.V. Shuryak, nucl-th/0110037.

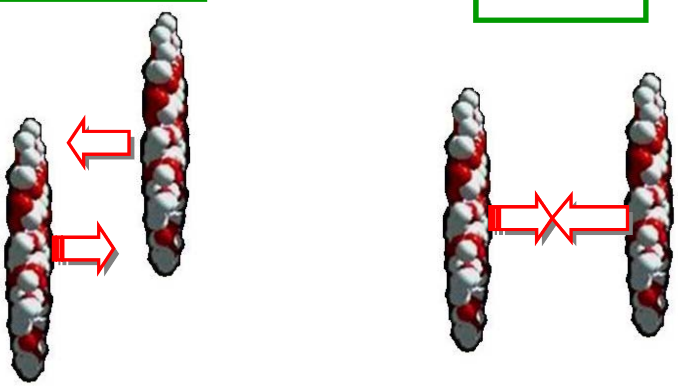
⇨Smooth dependence vs energy

Particle Density: integrated over time …

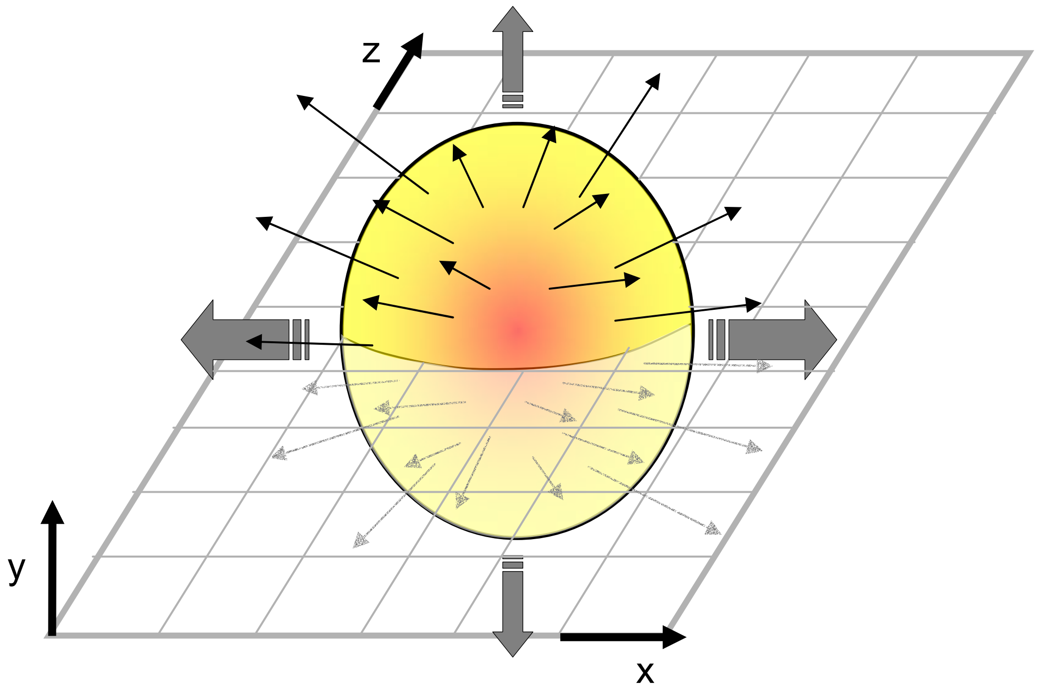


Peripheral

Central



Expanded fireball

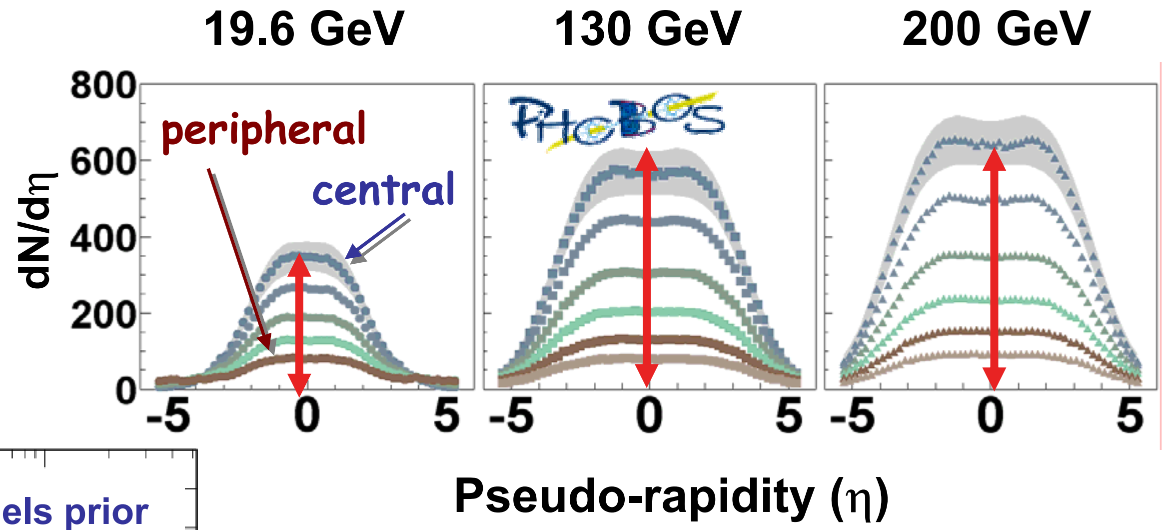


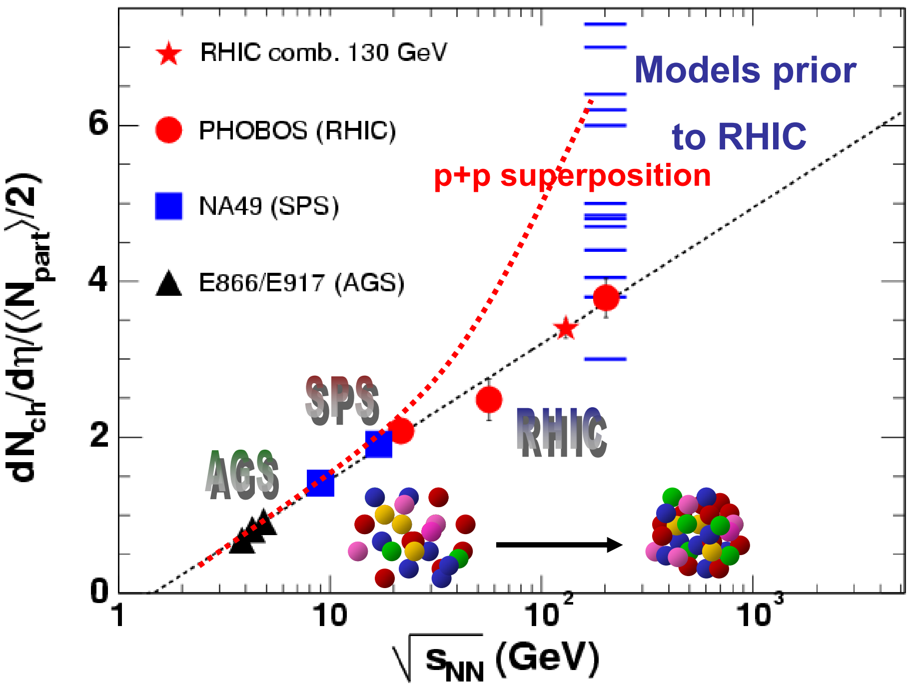
Particle emission dominated by the later stages

For correlations results, see Paul Chung (Thursday aft.)

Particle Density near Mid-Rapidity (|η|< 1)

How do RHIC colliding energies translate into mid-rapidity hadron production at RHIC ?





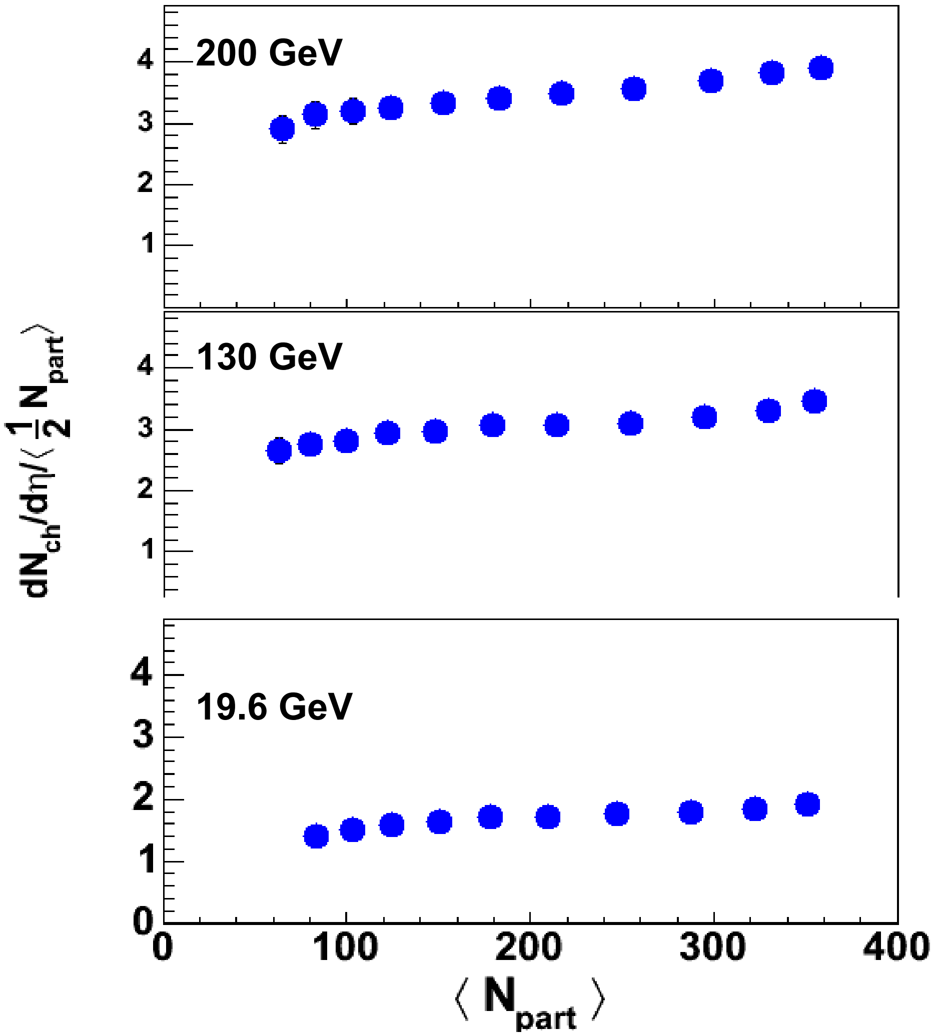
N_{part} scaling

Au+Au @ 200 GeV

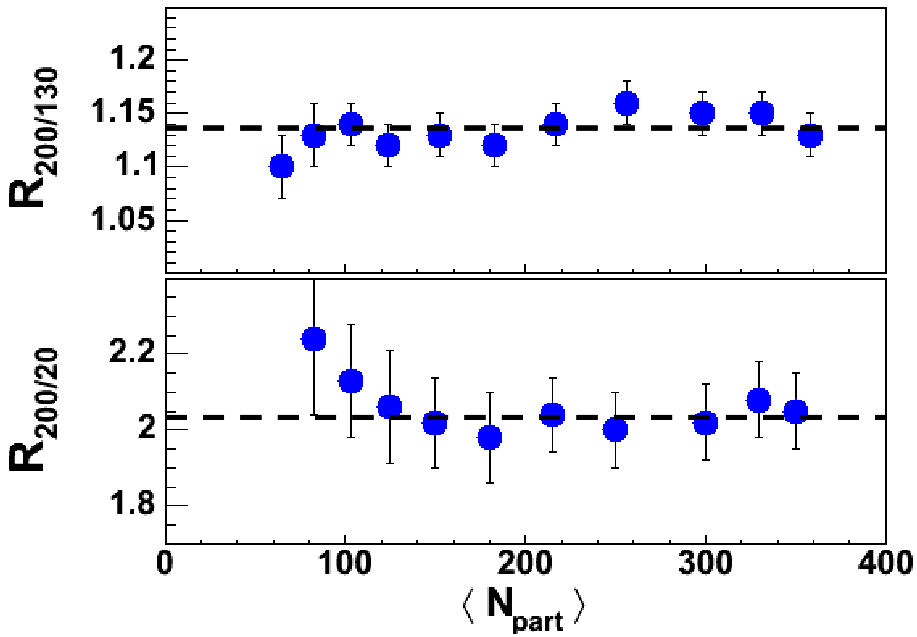
System: ε > 5 GeV/fm³

See talk from Rosa Anna Fini (this aft.)

Centrality Dependence on Particle Density (|η|< 1)

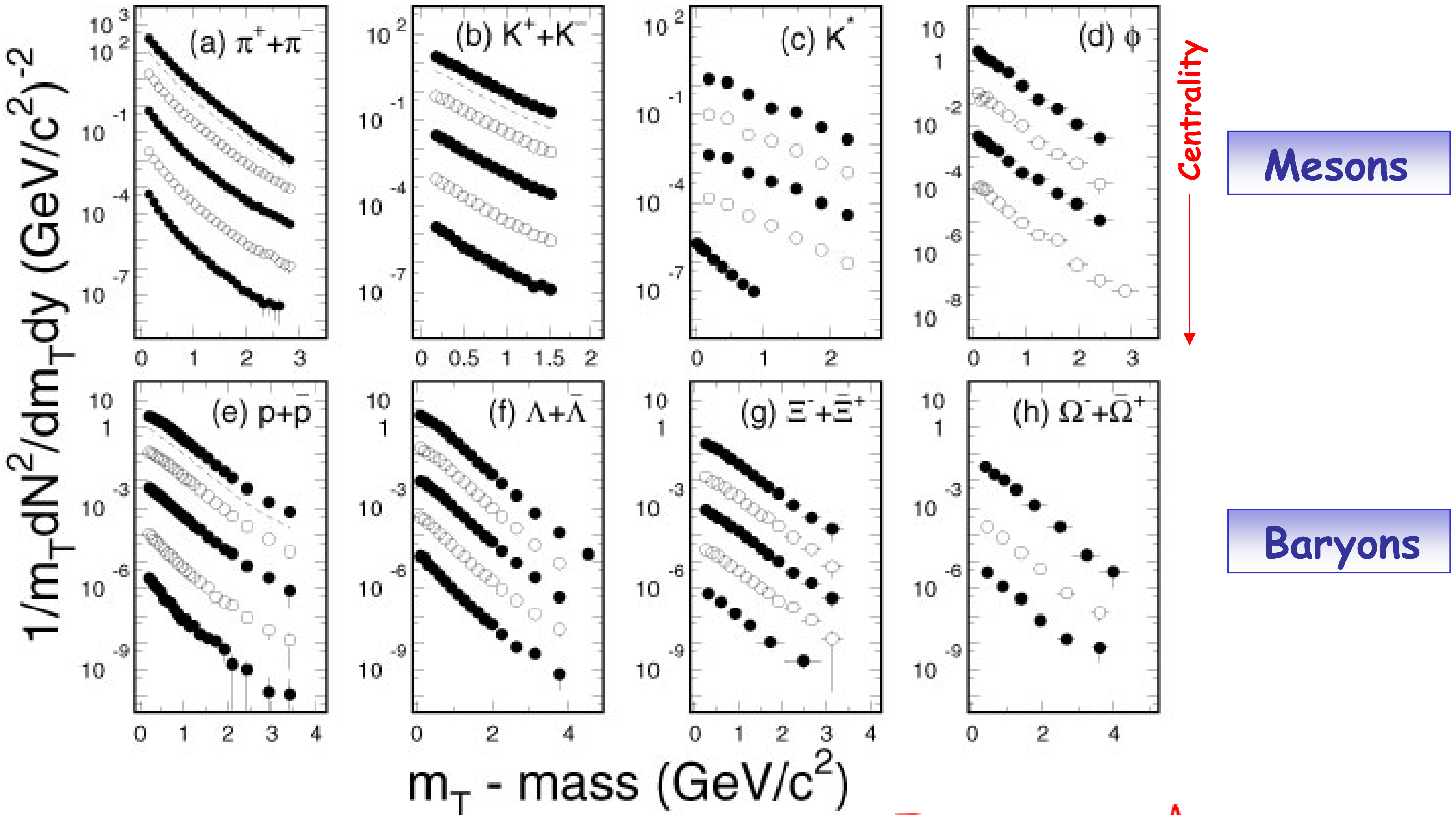


Results from PHOBOS



Absence of centrality dependence

Identified particle spectra at 200 GeV



Examples of particle spectra from both PHENIX and STAR

Thermal Description of the System: T_{ch} and μ_B

Statistical Thermal models describing the system at chemical freeze-out: assume an ideal hadron gas chemically and thermally equilibrated

$$\langle n_j \rangle = \frac{(2J_j+1)V}{(2\pi)^3} \int d^3p \left[e^{\sqrt{p^2+m_j^2}/T + \mu \cdot q_j/T} \pm 1 \right]^{-1}$$

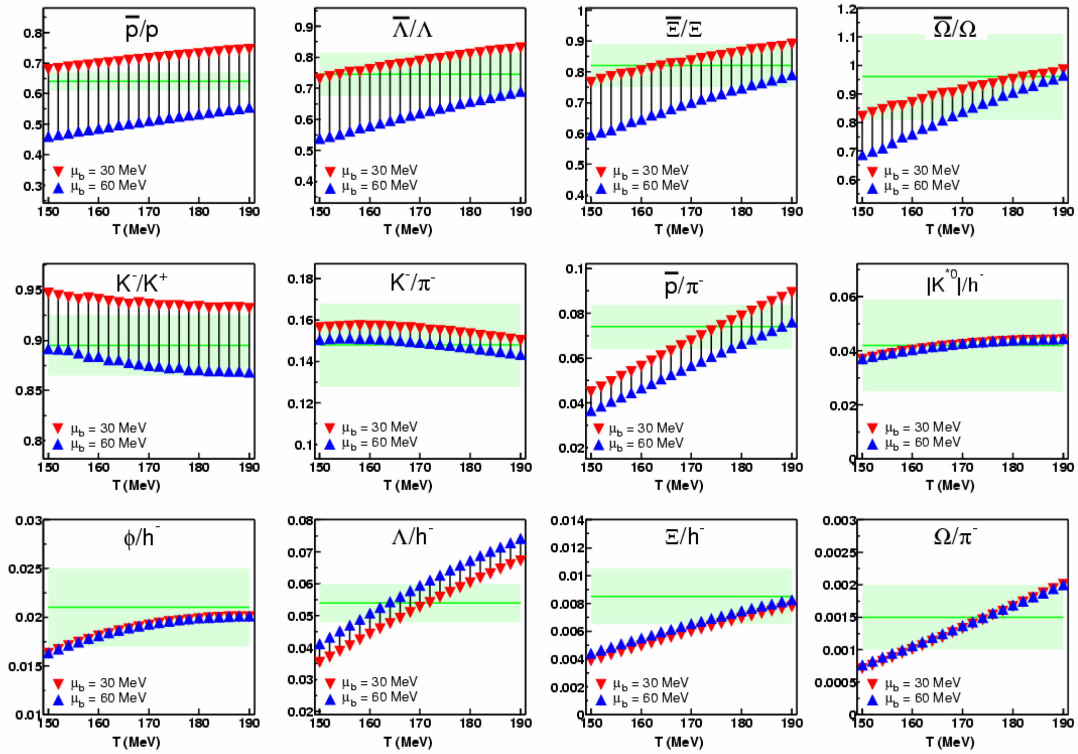
Measured Particle Ratios

(grand) canonical

partition function

density of particle

Baryo-chemical potential μ_B and Temperature T_{ch}



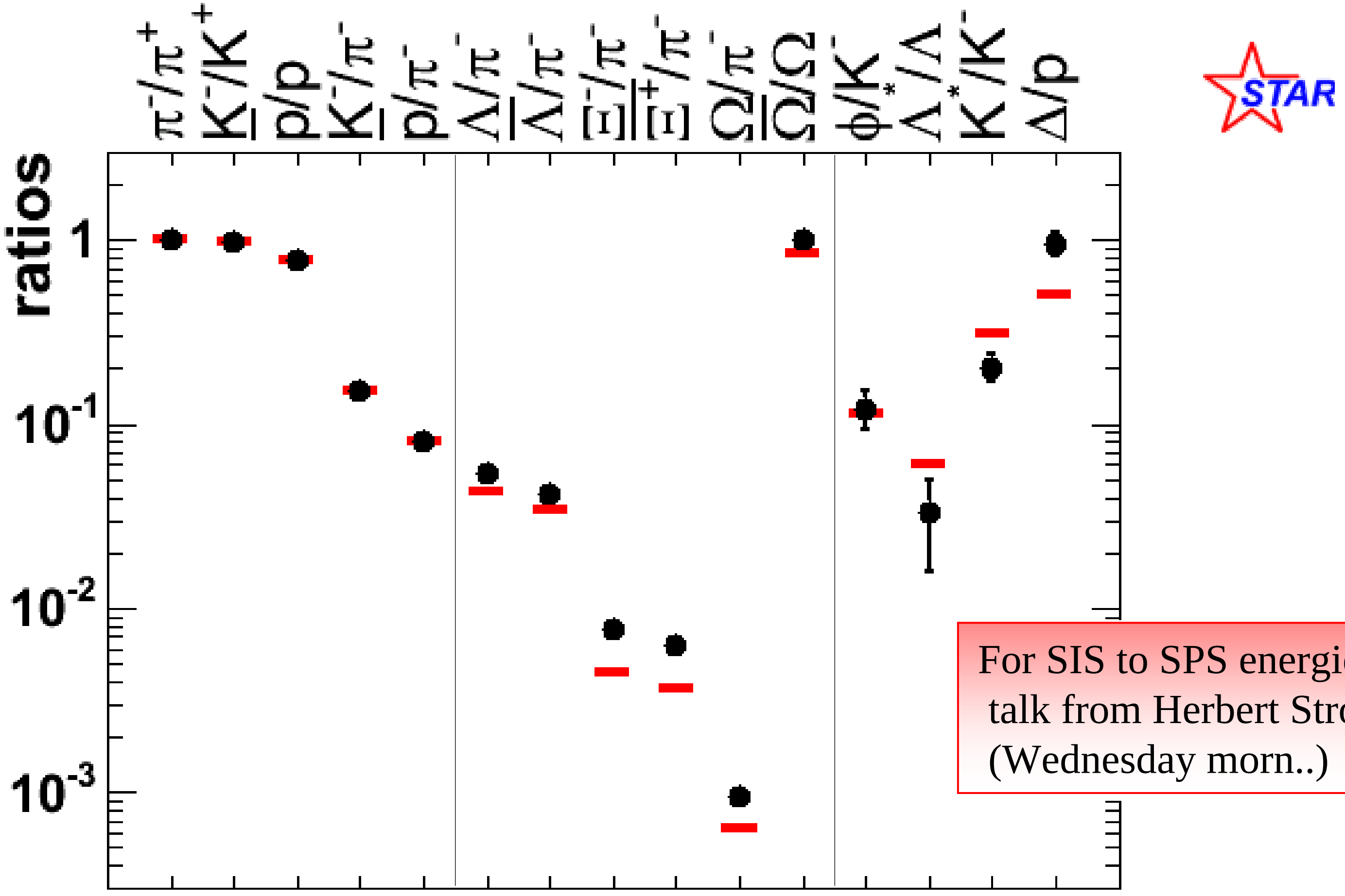
D. Magestro, J. Phys G28 (2002) 1745; updated July 21

Thermal Description at RHIC (200 GeV)

● Au+Au

Fit to

— π, K, p

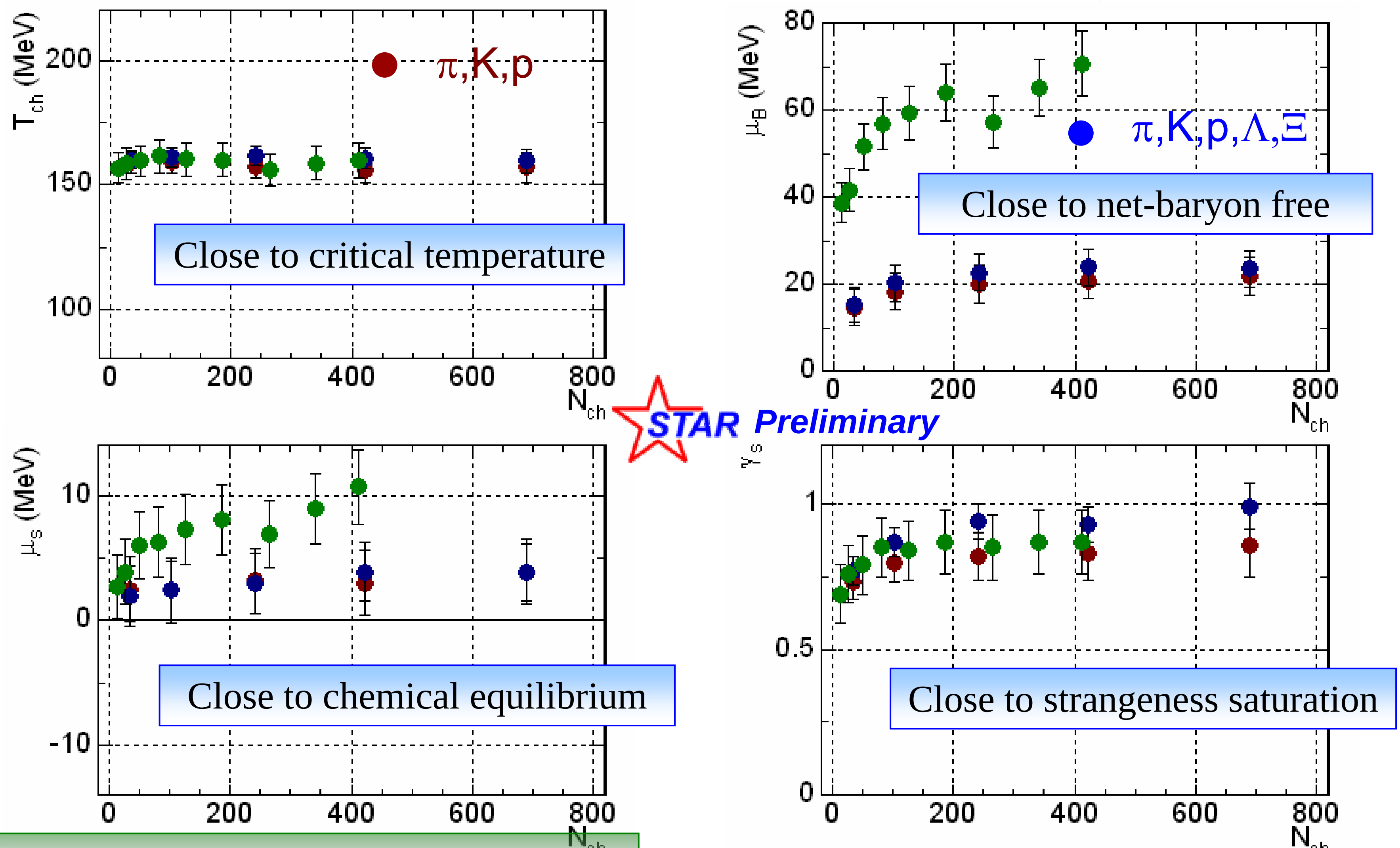


For SIS to SPS energies, talk from Herbert Stroebele (Wednesday morn..)

- Chemical freeze-out around 160 MeV, close to expected critical temperature;
- Deviations of the resonance yields compared to thermal model predictions indicative of hadronic phase (rescattering) after chemical freeze-out

Centrality and Energy Dependence of the Parameters

at 200 GeV and 62 GeV



See talk from Krzysztof Redlich (Tuesday morn.)

Energy dependence but small centrality dependence…

Strange Meson Production

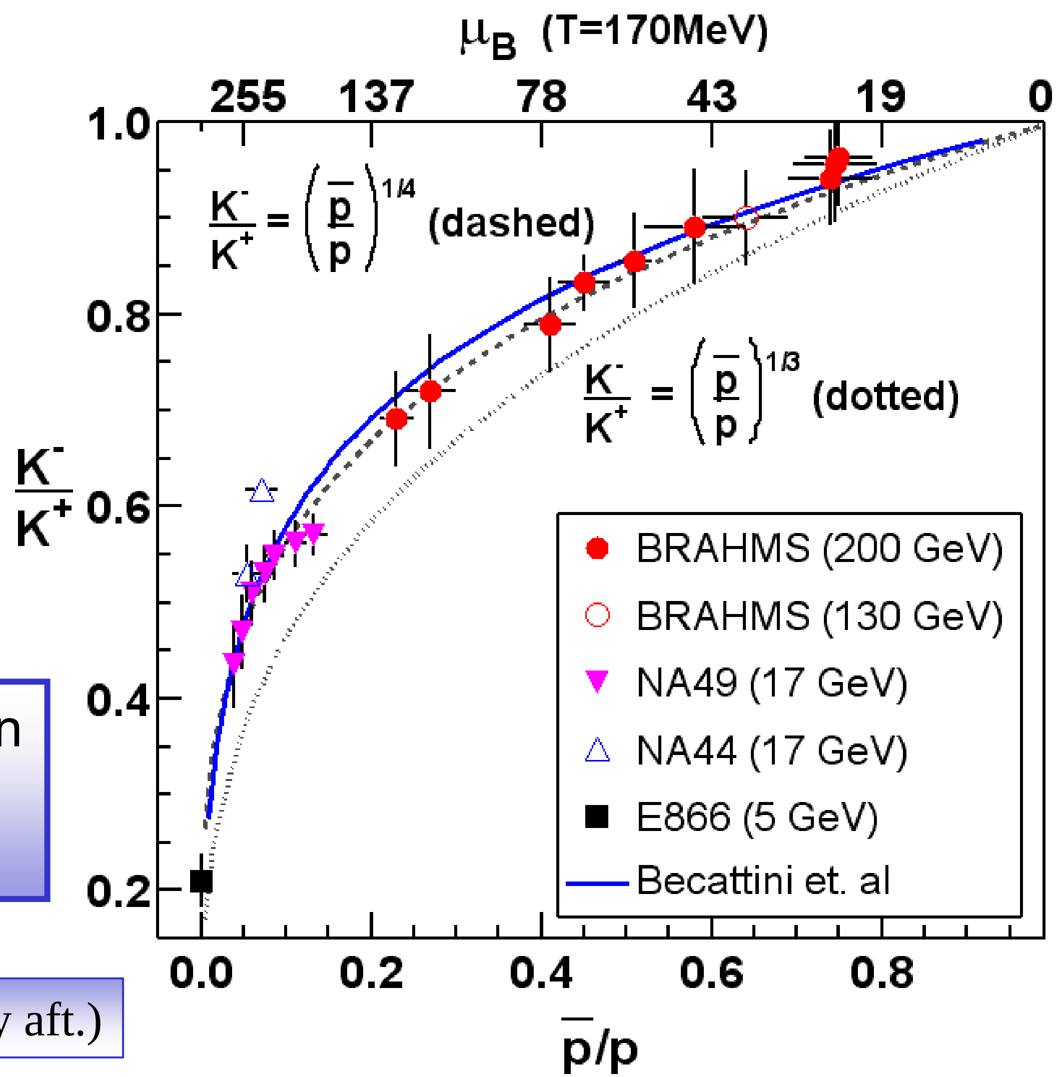
Results from BRAHMS

Kaons carry large percentage of strangeness content.

$K^- = \bar{u}s$

$K^+ = \bar{s}u$

Ratio (~ $\bar{u}/u$) shows pair production vs baryon transport.



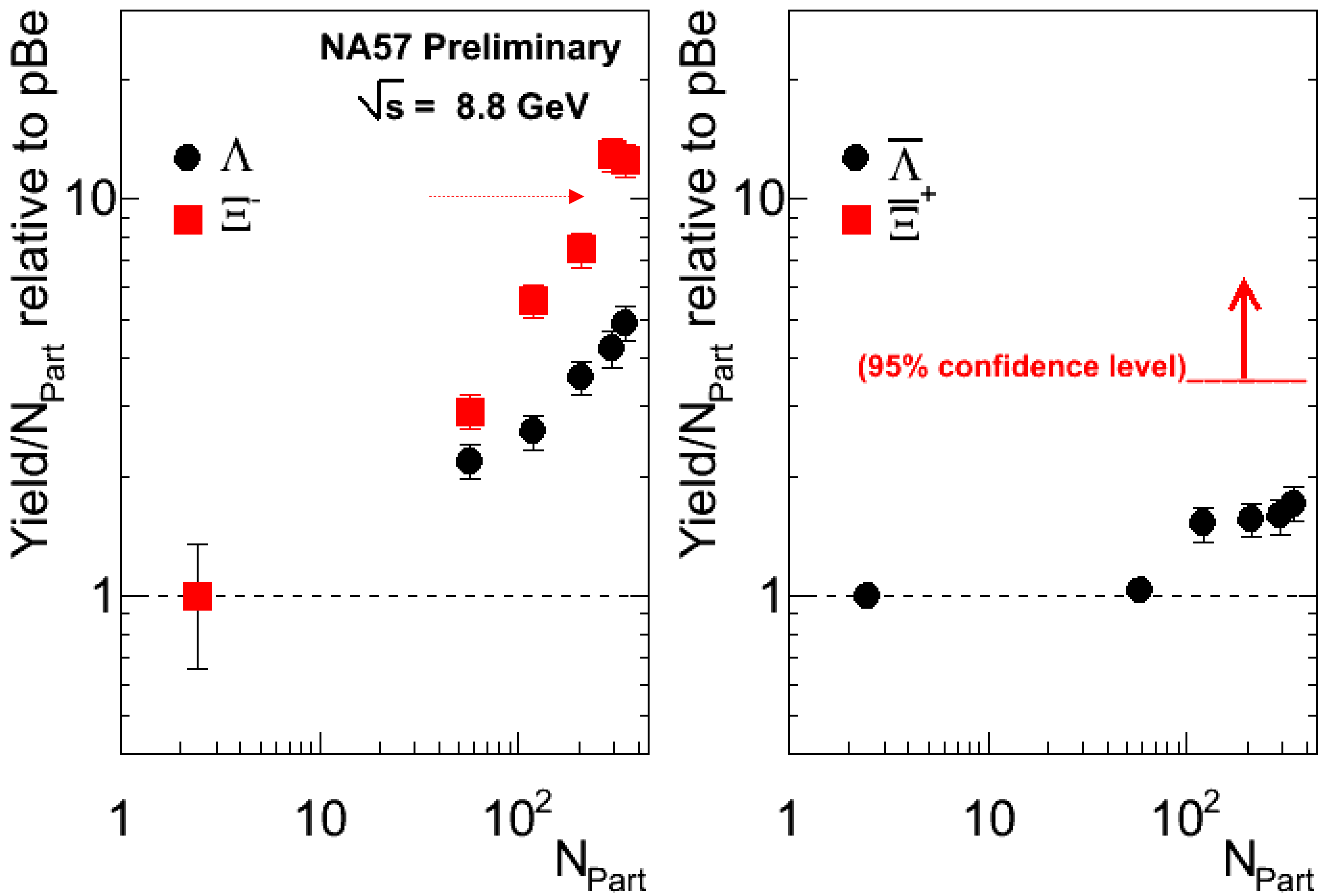
By varying rapidity range, we can study many different physics regions (mapping μ_B)

See talk from Dieter Roehrich (Thursday aft.)

Strange Baryon Enhancement at CERN : NA57

Heavy ions yields normalized to elementary collisions at same energy

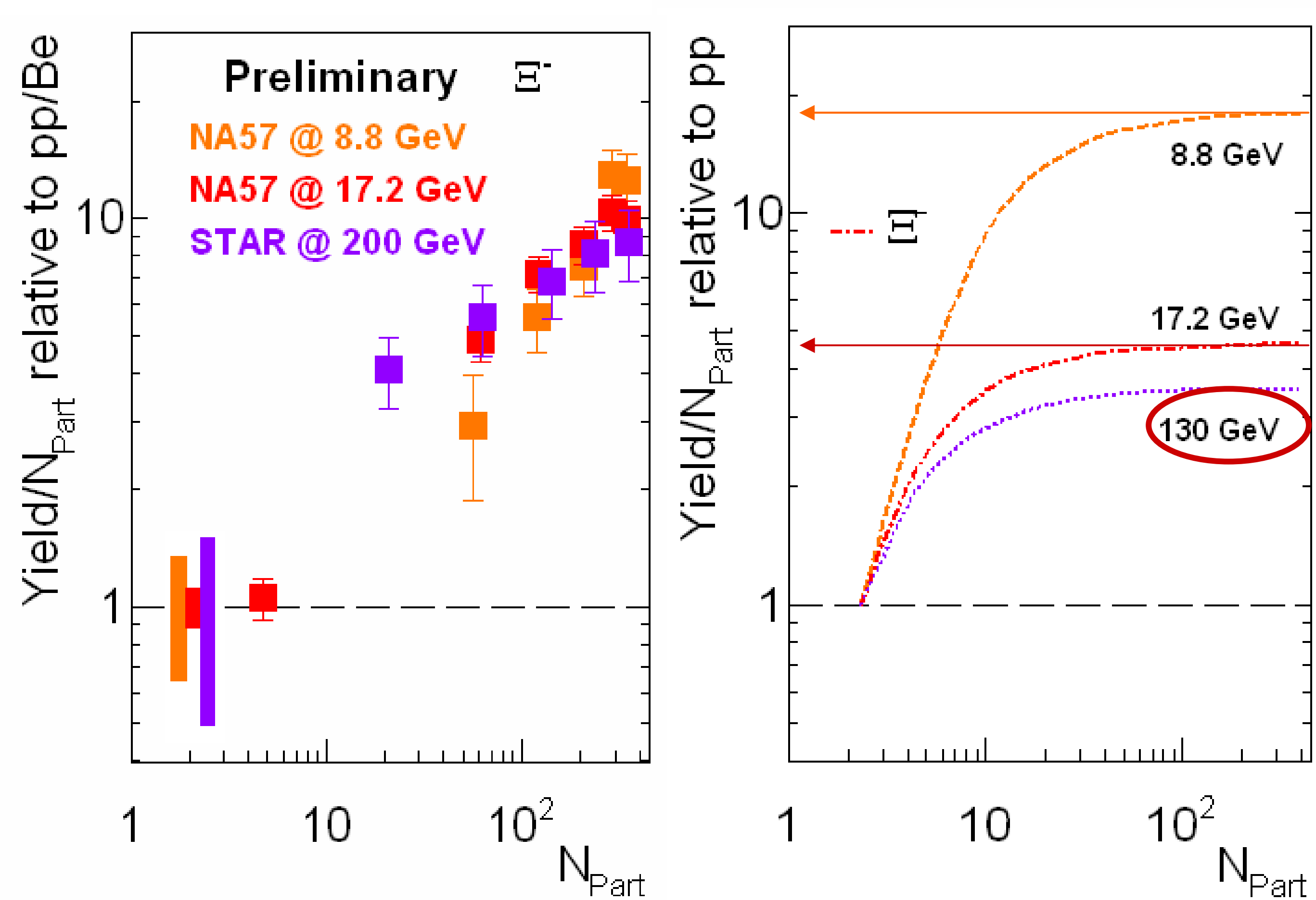
See talk from Helena Bialkowska (Friday aft.)



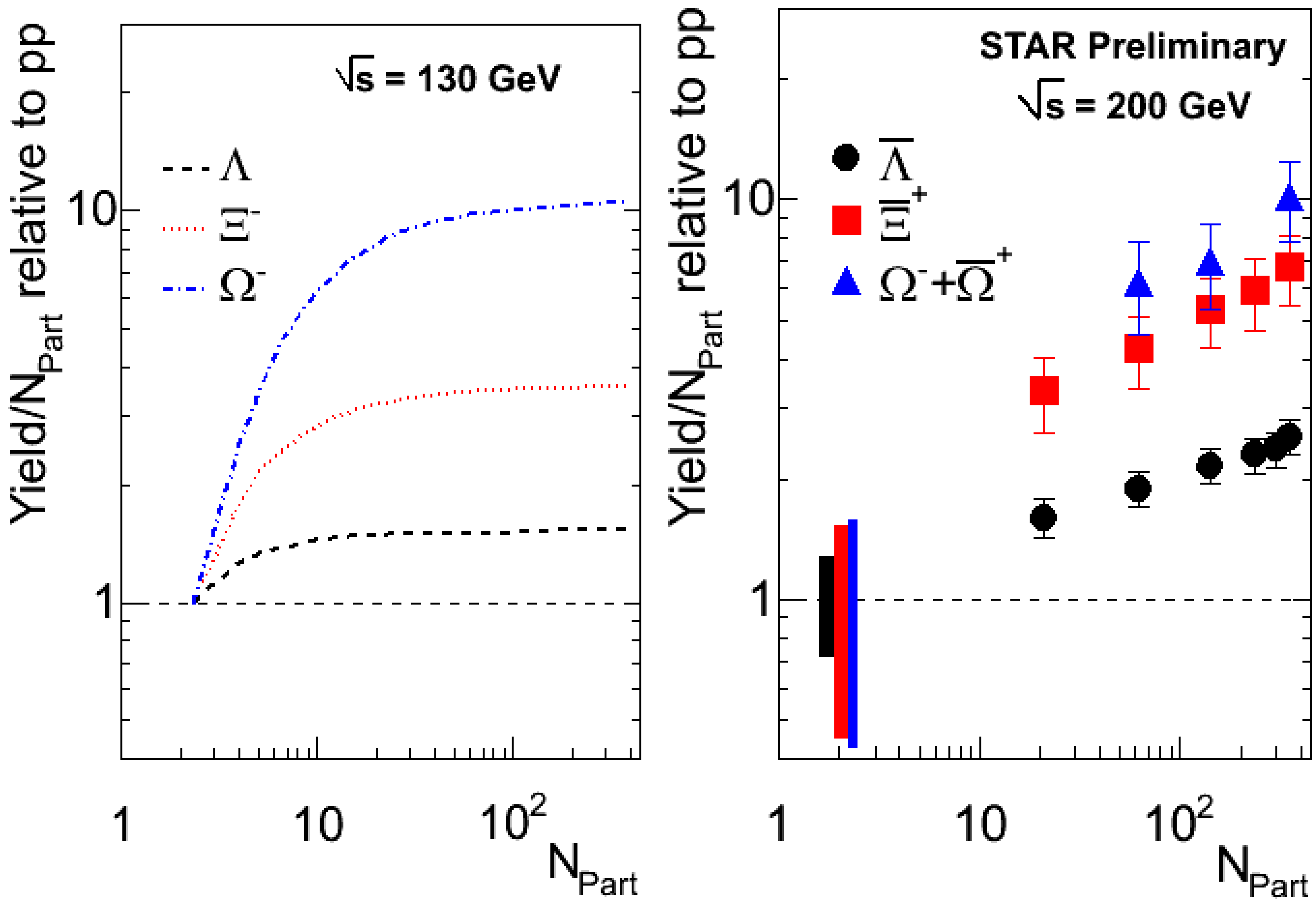
Is the scaling correctly reproduced and is the correlated volume the same for all hyperons ?

…or Phase space Suppression

[Tounsi & Redlich: hep-ph/0111159]



Phase space suppression smaller at RHIC



- "Enhancement" @ RHIC ~ @ SPS
- Need some new "predictions" ...
- Correlation volume not well modeled by N_{part}

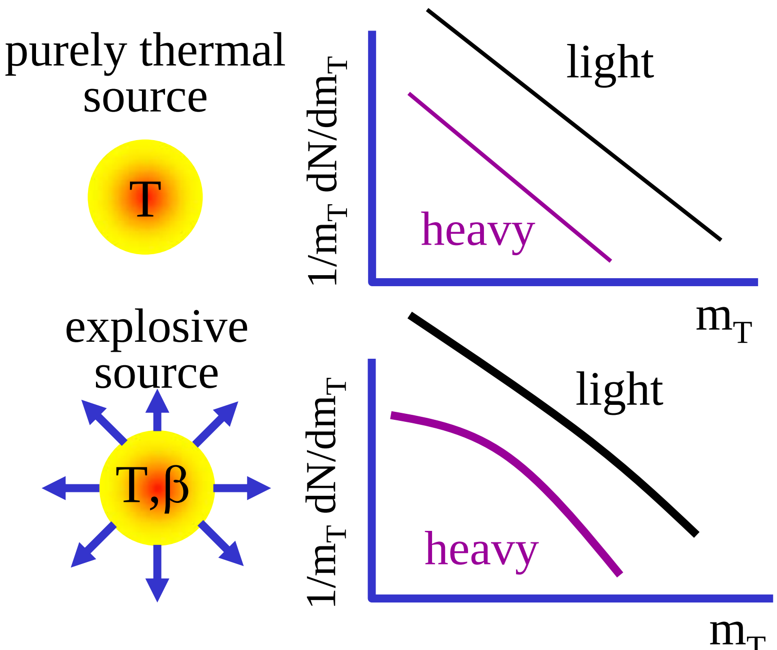
Hydrodynamics and Description of Thermal Spectra

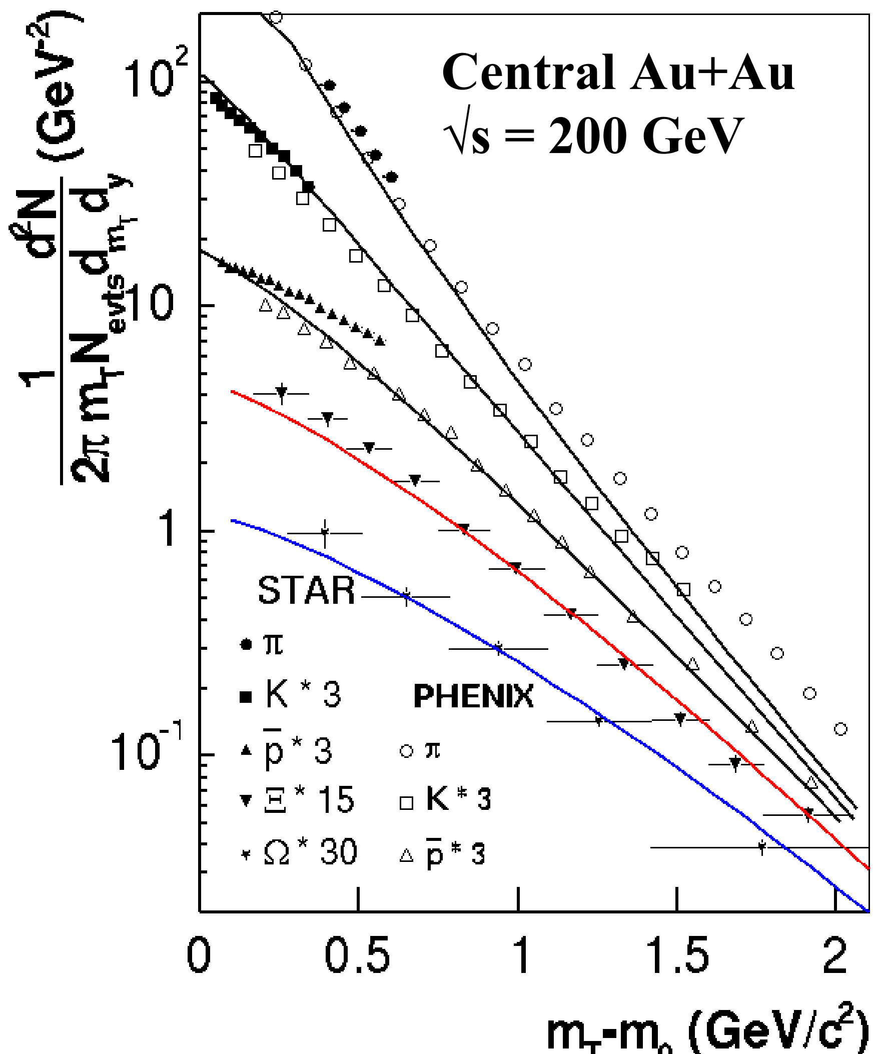
- Final state spectra at Thermal Freeze-Out can be modeled by ideal hydrodynamics

Especially mass dependence with:

- **"temperature" T_{kin}**
- **collective radial (transverse) flow β_T**

See talk from Boris Tomasik (Friday morn.)

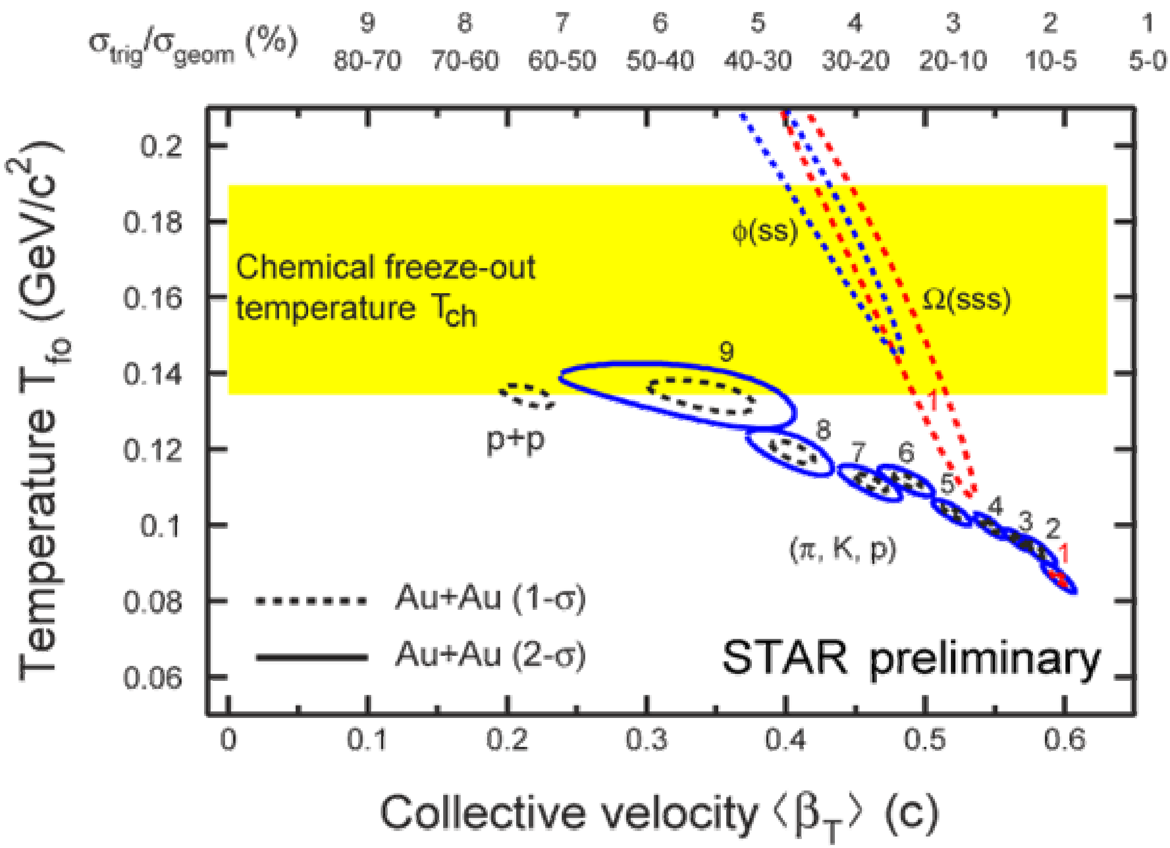




Hydro (P. Kolb & U. Heinz) with initial flow kick

Kinetic Freeze-out (*) at 200 GeV

(*) with the "poor experimentalists'hydro": Blast-wave fit !



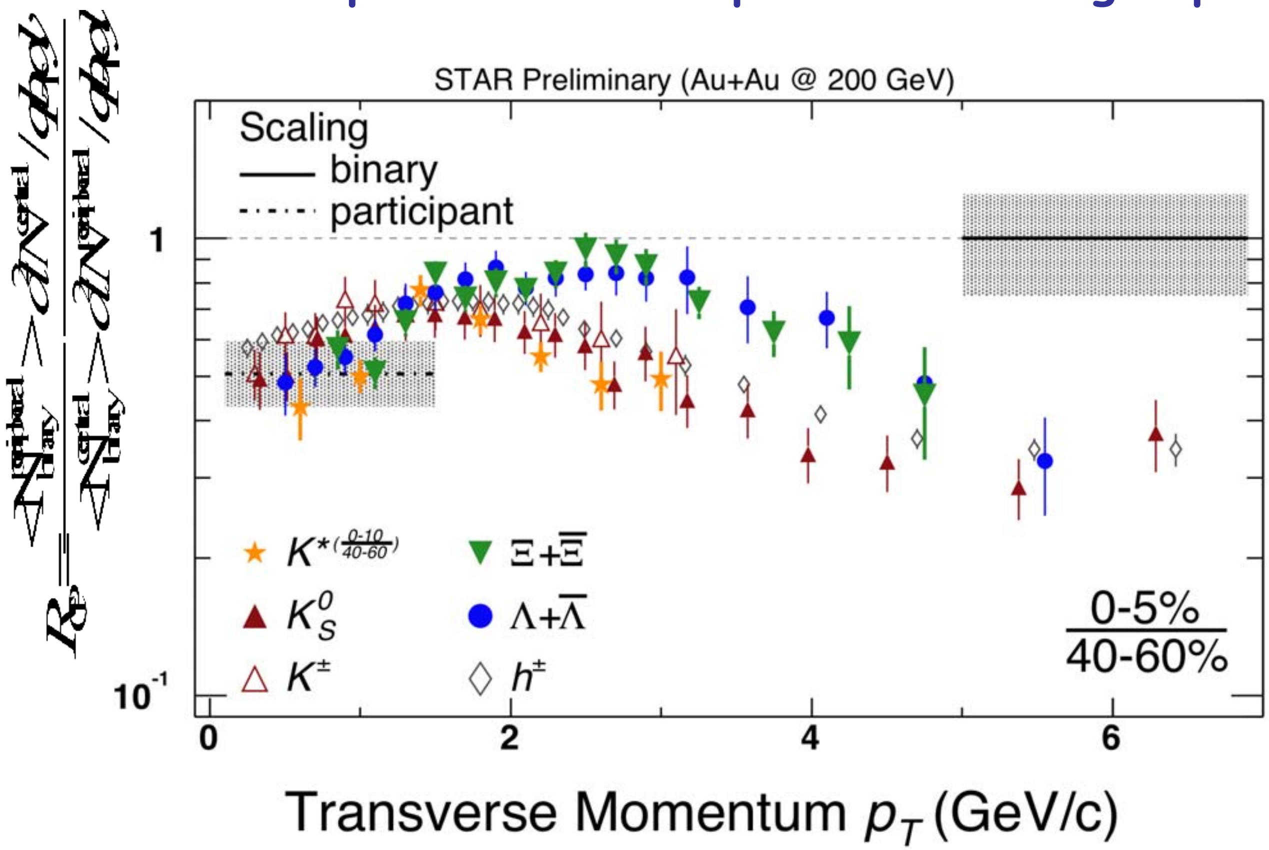
– π,K,p: T_{kin} decreases with centrality, Ξ: T_{kin} = const

–ϕ, Ξ and Ω with low hadronic cross section but strong radial flow

–See talk from Magali Estienne (Friday aft.)

Identified particles at intermediate to high-p_T

Comparison of the shapes of the spectra between different centrality classes: Species can be separated in two groups…



- **Mesons**
- **Baryons**

Apparently not a simple mass effect (change in the shape of the spectra due to radial flow)

See talk from Rene Bellwied (Friday aft.)

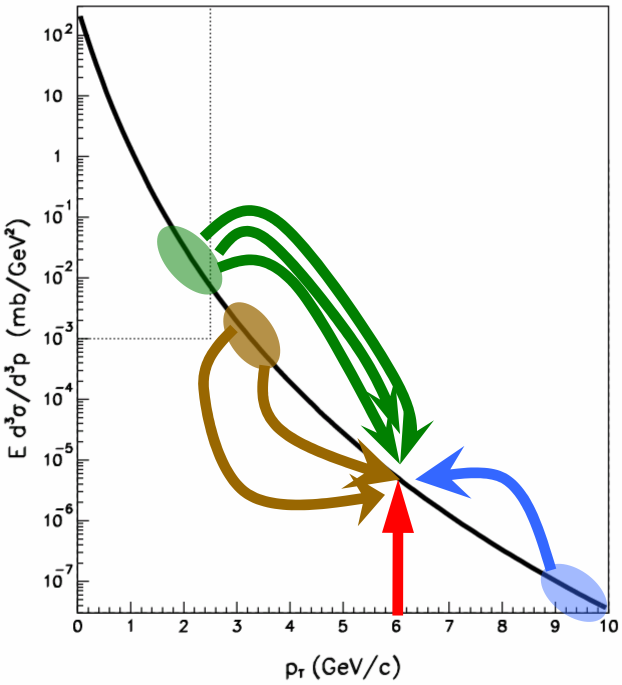
Information about hadronization process(es) ?

Coalescence: possible mechanism at intermediate p_T

- The in vacuo **fragmentation** of a high momentum quark to produce hadrons *competes* with the in medium recombination of lower momentum quarks to produce hadrons

See talk from Peter Levai (Thursday morn.)

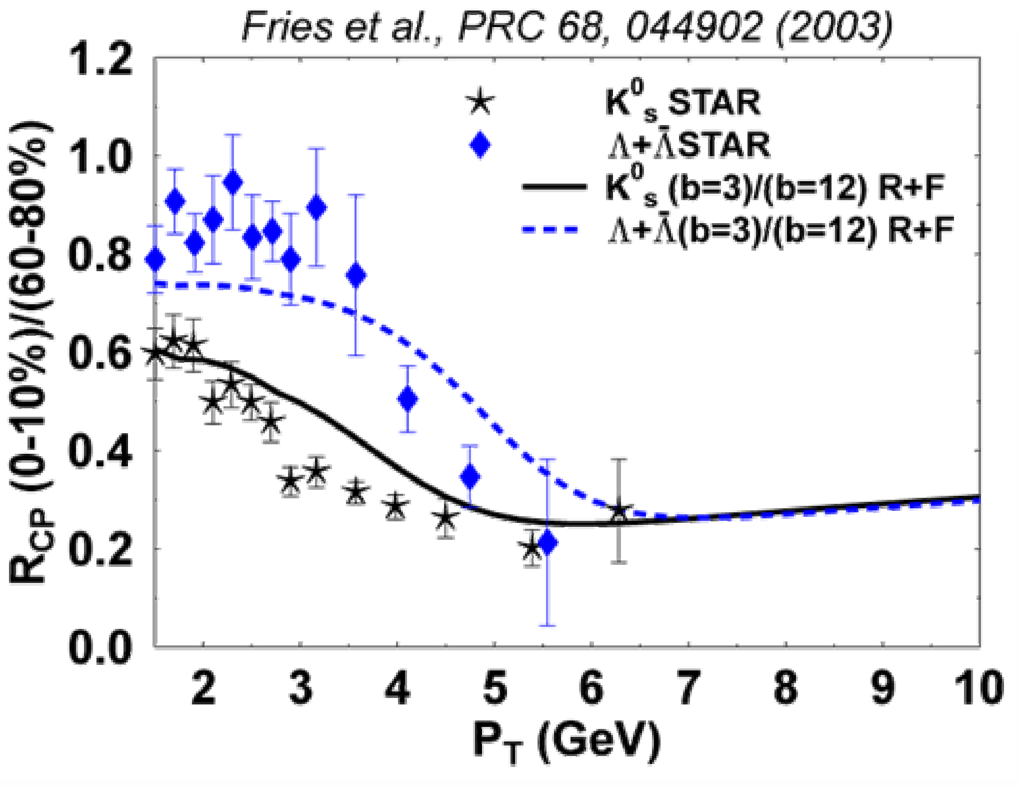
- Example:
  - Fragmentation: $D_{q\rightarrow h}(z)$
    - produces a 6 GeV/c π from a 10 GeV/c quark
  - Recombination:
    - produces a 6 GeV/c π from *two* 3 GeV/c quarks
    - produces a 6 GeV/c proton from *three* 2 GeV/c quarks

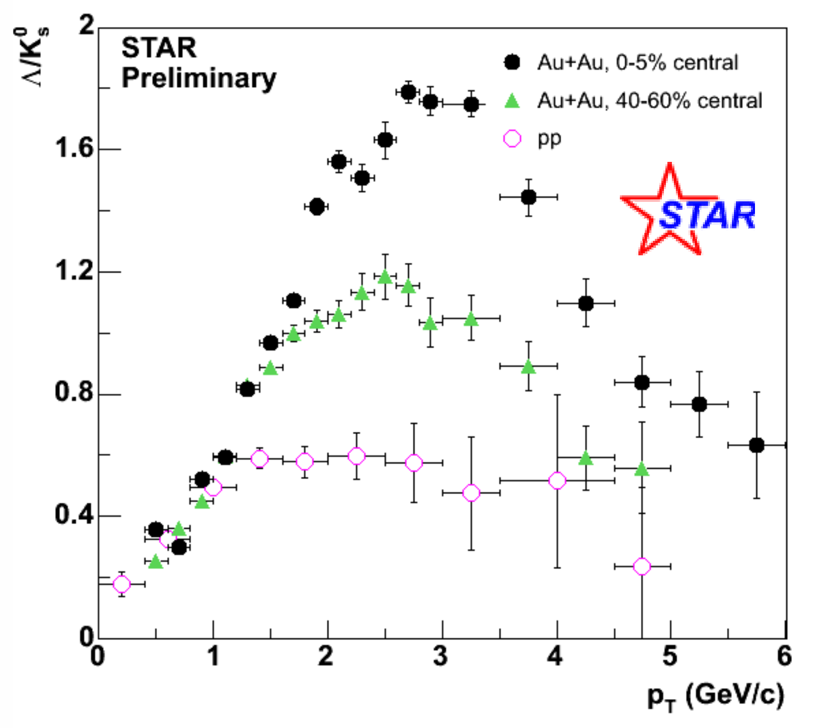


...requires the assumption of a thermalized parton phase... (which) may be appropriately called a quark-gluon plasma

Fries, et al, PRC 68, 044902 (2003)

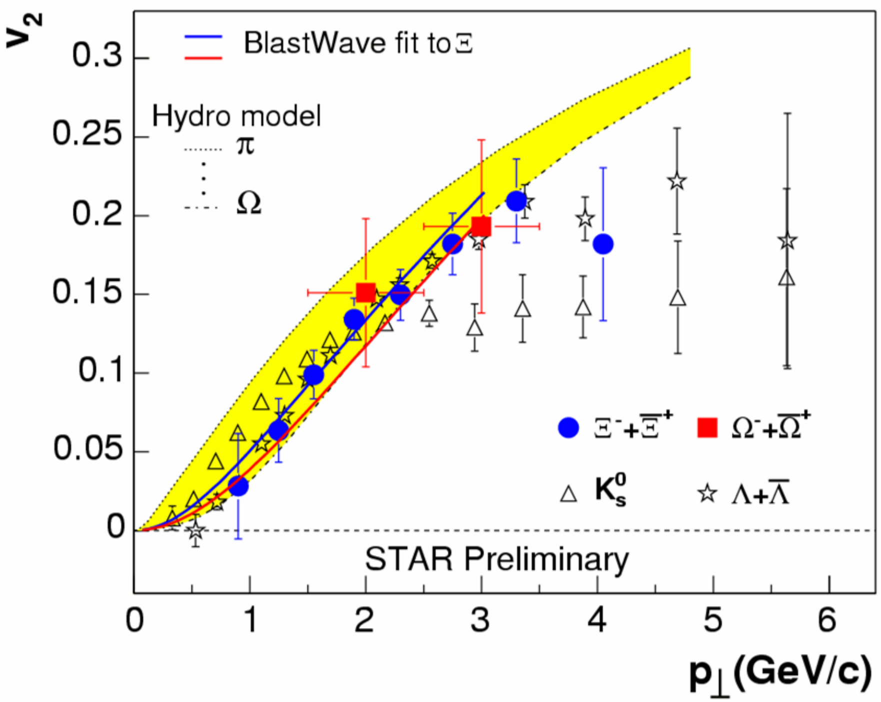
Baryon Enhancement at intermediate p_T

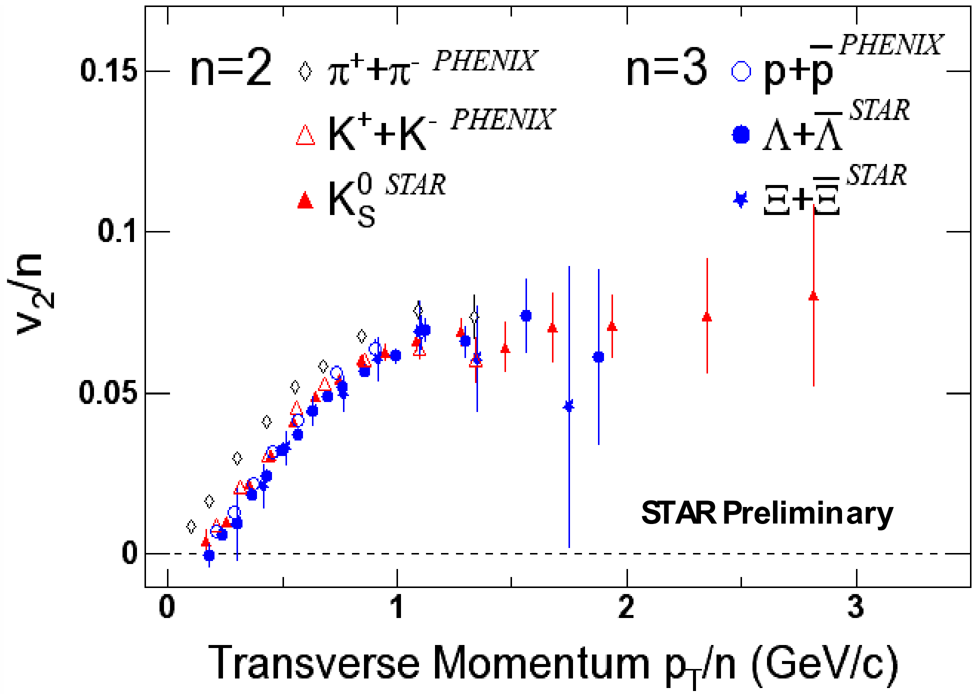




For different models:
D. Molnar, S.A. Voloshin Phys. Rev. Lett. 91, 092301 (2003)
V. Greco, C.M. Ko, P. Levai Phys. Rev. C68, 034904 (2003)
R.J. Fries, B. Muller, C. Nonaka, S.A. Bass Phys. Rev. C68, 044902 (2003)
Z. Lin, C.M. Ko Phys. Rev. Lett. 89, 202302 (2002)

Identified Elliptic flow at intermediate to high p_T



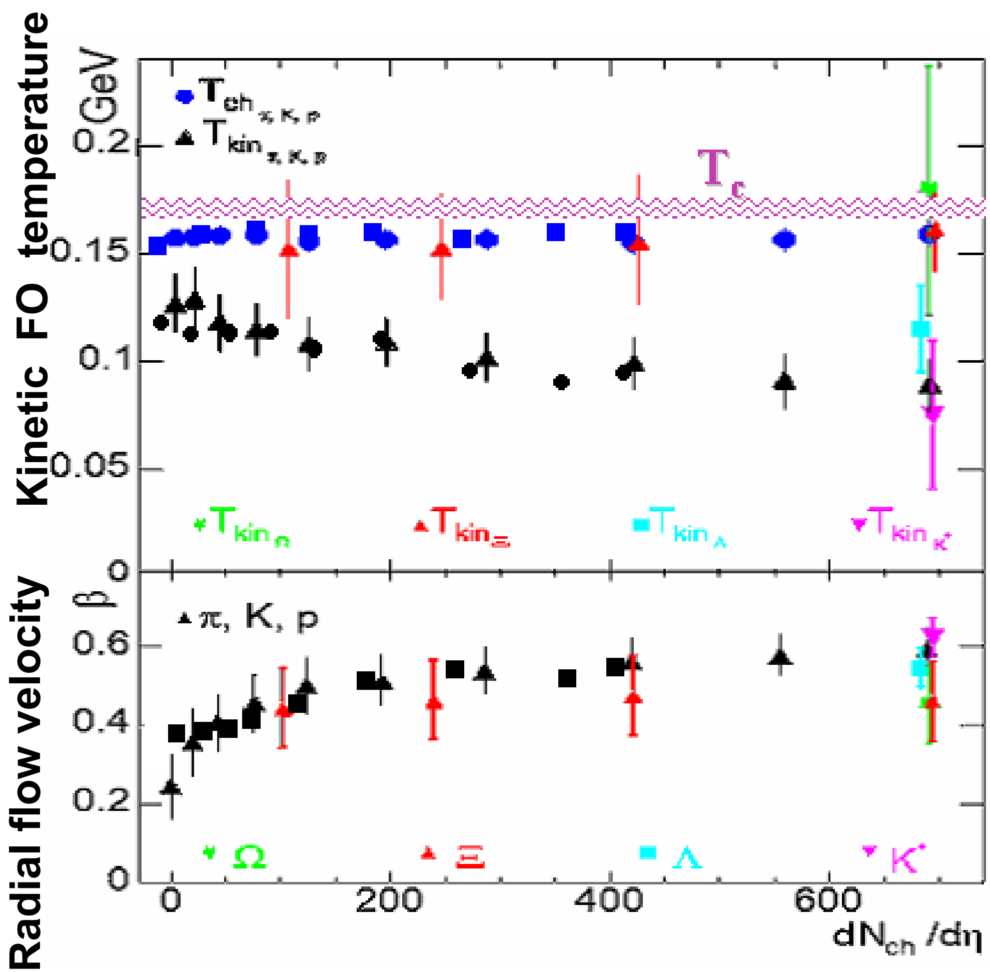


⇨ **Even multi-strange particles show an important elliptic flow;**
⇨ **Using strange particles to probe B/M differences over a large p_T range.**

⇨Scaling wrt constituent quarks (as suggested by coalescence models) seems to provide a consistent picture

See talk from Magali Estienne (Thursday morn.) and Scott Pratt (this aft.)

Global picture of the System Evolution



Reminder: LQCD with $\mathbf{T_c}$ = 160±10 MeV

Expansion and Cooling

$T_{kin} \sim T_{ch} \sim 160$ MeV → $\beta \sim 0.45$

multi-strange

$T_{kin} \sim 90$ MeV, $\beta \sim 0.6$

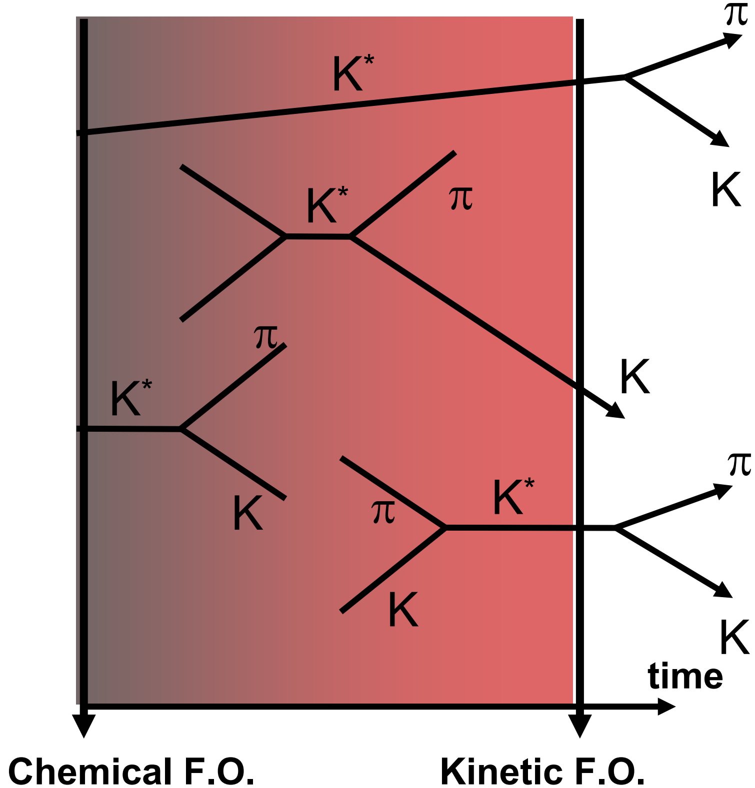
rescattering

Chemical FO close to hadronization

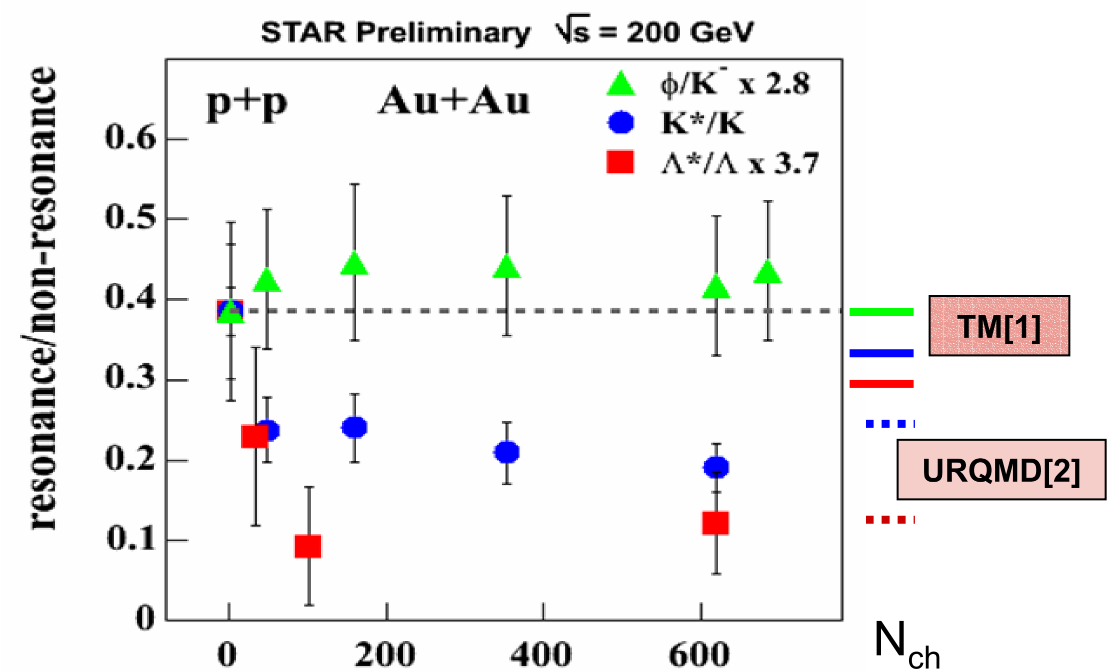
Strong Collective Behaviour at hadronization

Look for rescattering indirect measures

Rescattering and Regeneration of Resonances



- Initial Production Yields at Chemical F.O;
- In-medium decay & rescattering of decay products;
- Rescattering may lead to regeneration;
- Competition between the two effects (cτ) !



Using resonance for probing evolution of the system between both F.O.

[1] P. Braun-Munzinger et.al. PLB 518(2001) 41
D. Magestro, private communication.
[2] M. Bleicher and J. Aichelin Phys. Lett. B530 (2002) 81-87.
M. Bleicher, private communication.

Resonance Resonance $e^{-\Delta t/\tau}$
Stable T_{fo} Stable T_{ch}

Then >4fm between T_{ch} and T_{kin}

Conclusion

- At RHIC, reaching the limits of hydrodynamics may imply early local thermalization.
  - -Ambiguities due to initial conditions and the choice of EoS;
  - -Systematics (more statistics), energy/system scans and PId.

- Multiplicity distributions scale well with N_{part}. Data indicate a linear rise from AGS to RHIC but show no centrality dependence.
  - - Rapidity dependencies & PId: more constraints on the system evolution.

- Thermal description seems to imply that chemical and thermal (local) equilibrium is reached and that hadrons are born into equilibrium.
  - - But physics is in the details (strange,heavy): small centrality dependence.

- Constituent quark scaling suggests collectivity builds up during a pre-hadronization stage.
  - - Will this picture survive an energy scan ?

- Rescattering cannot be ignored: $\Delta t_{(kin-ch)} > 4 fm/c$.

Outlook

Hadronic observables show important hints of thermalization at the very early stages of the fireball evolution. Collective motion is such that it is hard to believe it is developed at the hadronic level only.

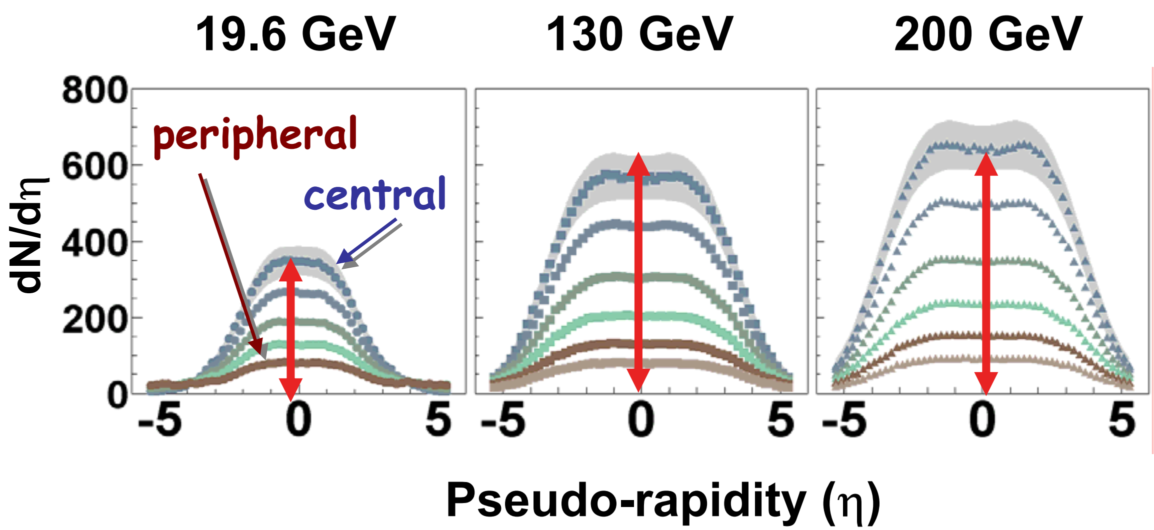
Understanding the details will provide the tools to go to the next level: from hints to proofs. Many ongoing analysis…

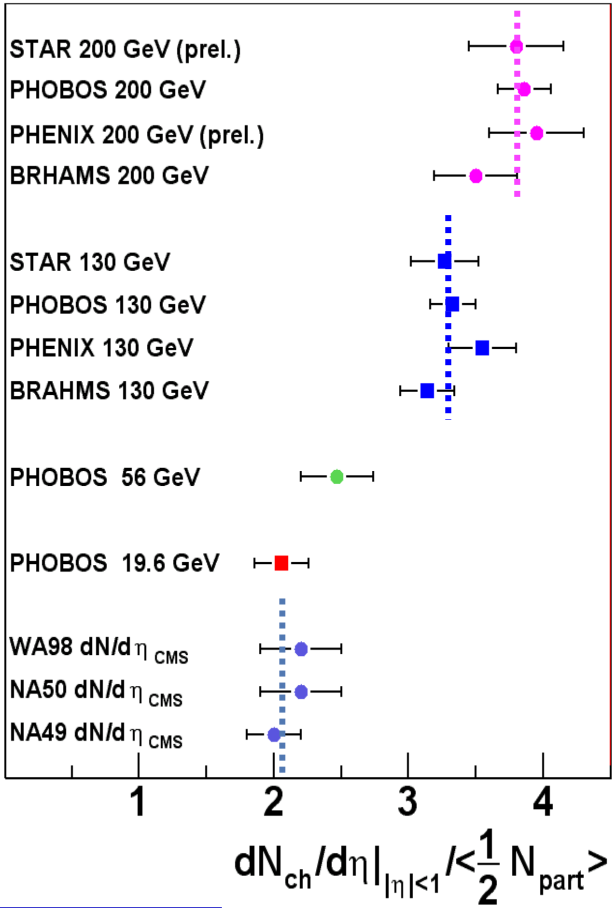
It is just starting…

Particle Density near Mid-Rapidity (|η|< 1)

How do RHIC colliding energies translate into mid-rapidity hadron production at RHIC ?

- Results from PHOBOS





Nice agreement between all four experiments at RHIC and between SPS @ 17.2 GeV and RHIC @ 19.6 GeV

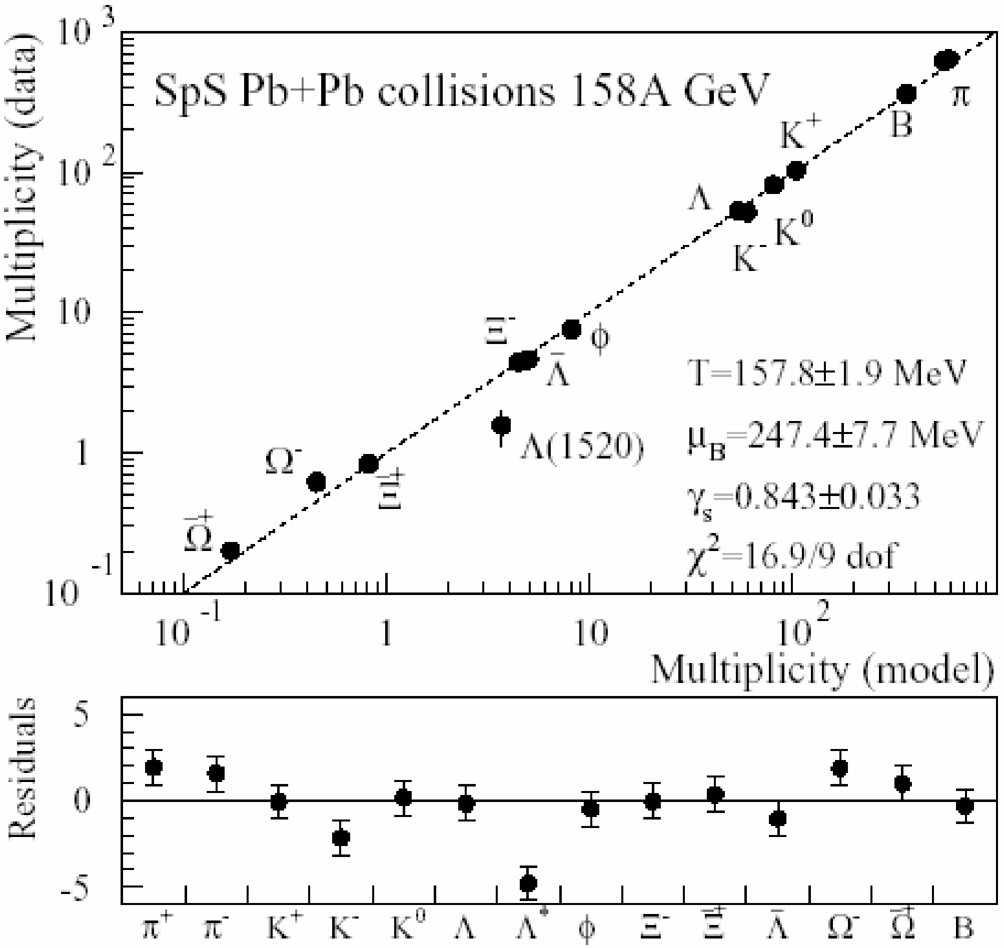
Thermal Description at the top SPS energies

[F. Becattini et al, hep-ph/0310049]

T_{ch} = 158 ± 2 MeV

γ_s = 0.84 ± 0.03

μ_B = 247 ± 8 MeV



T_{ch} at SPS close to T_c predicted by LQCD for the phase transition.

Thermal Description at RHIC (200 GeV)

Au+Au

● **STAR**

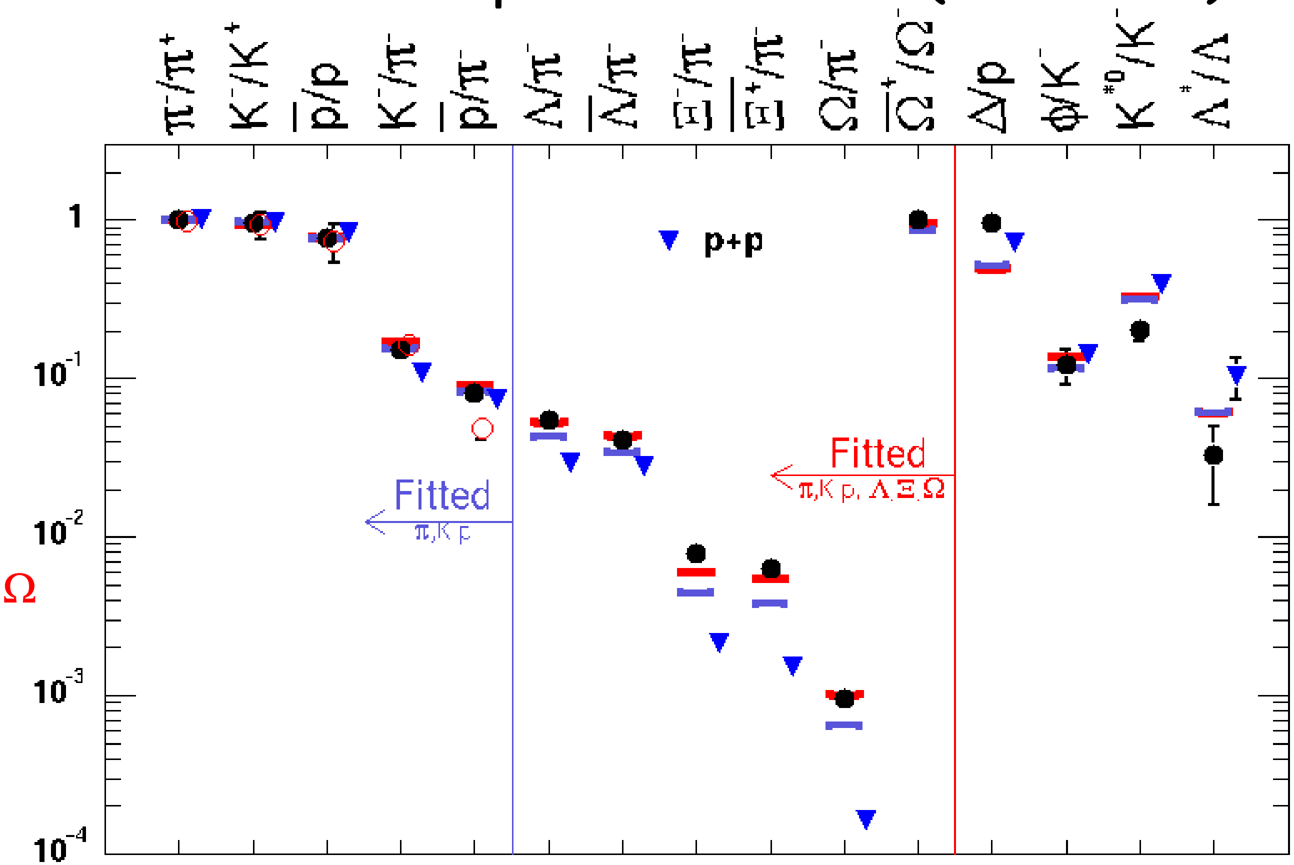
○ **PHENIX**

Fit to

— **p, K, p**

— **p, K, p, Λ, Ξ, Ω**

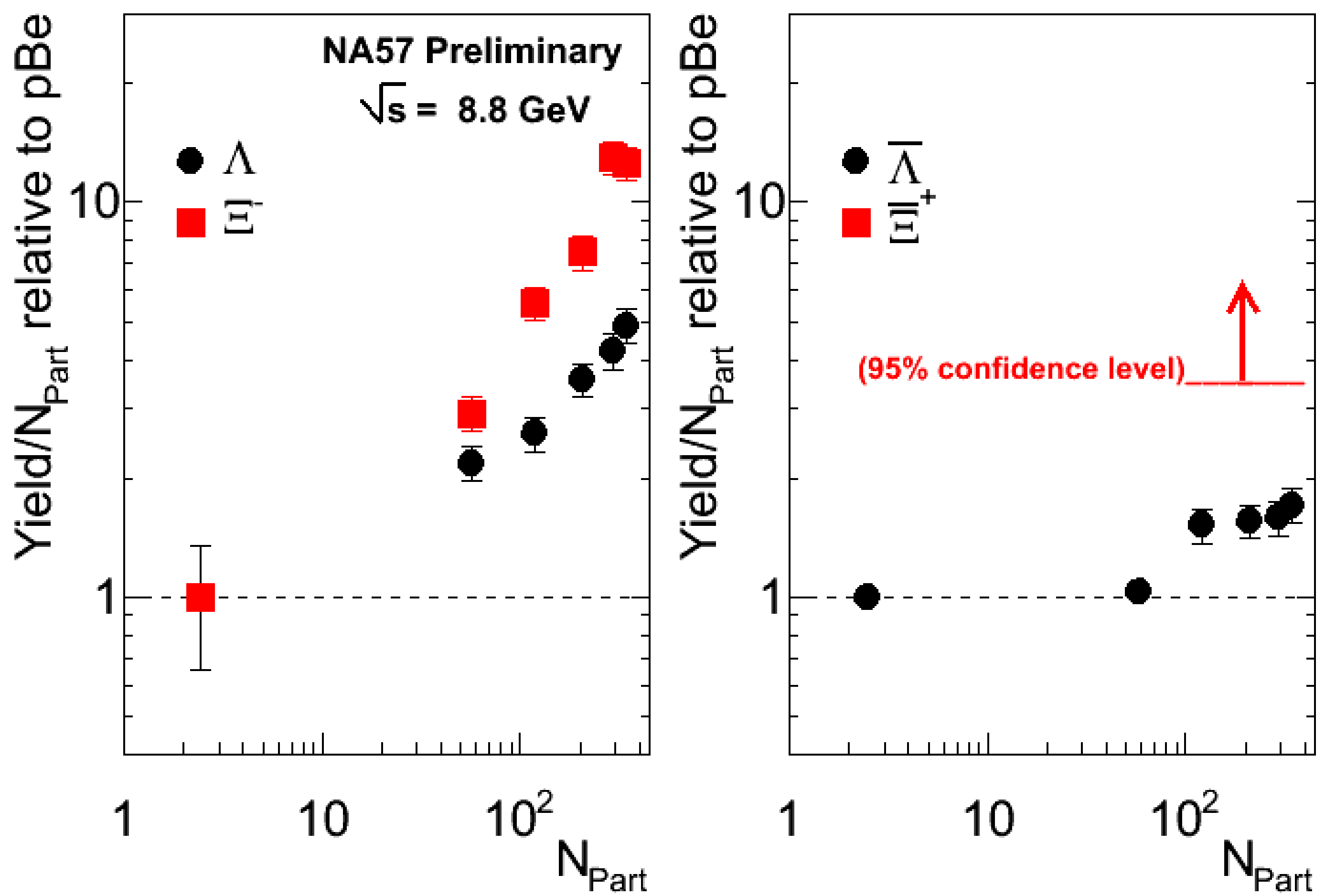
▼ **p+p**



- Chemical freeze-out around 160 MeV, close to expected critical temperature;
- Particle ratios similar in pp for most abundant species;
- Deviations of the resonance yields compared to thermal model predictions indicative of hadronic phase (rescattering) after chemical freeze-out

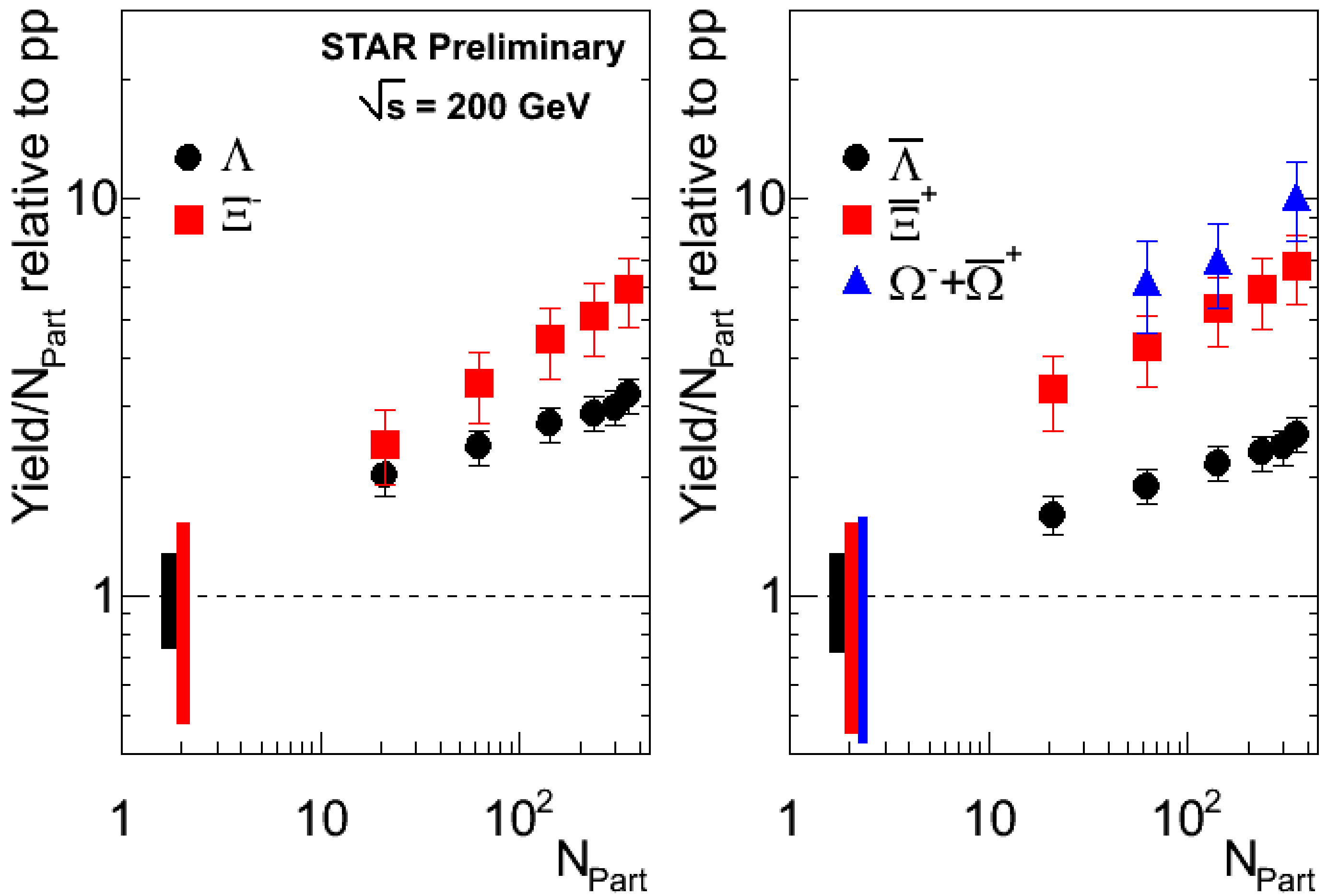
Strange Baryon Enhancement at CERN : NA57

Heavy ions yields normalized with elementary collisions at same energy



Is the scaling correctly reproduced and is the correlated volume the same for all hyperons ?

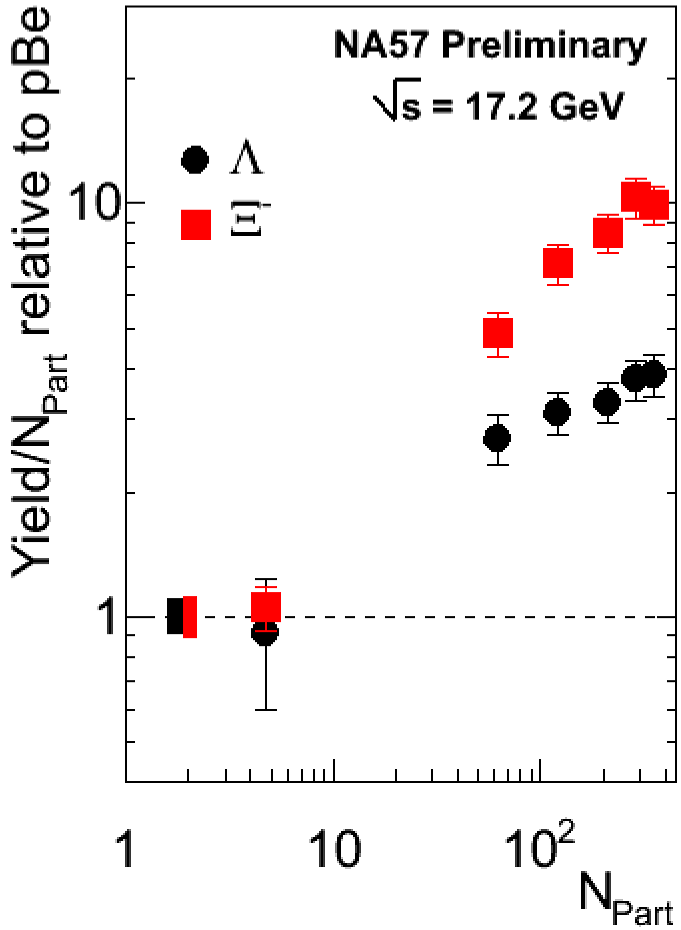
Strange Baryon Enhancement at RHIC : STAR

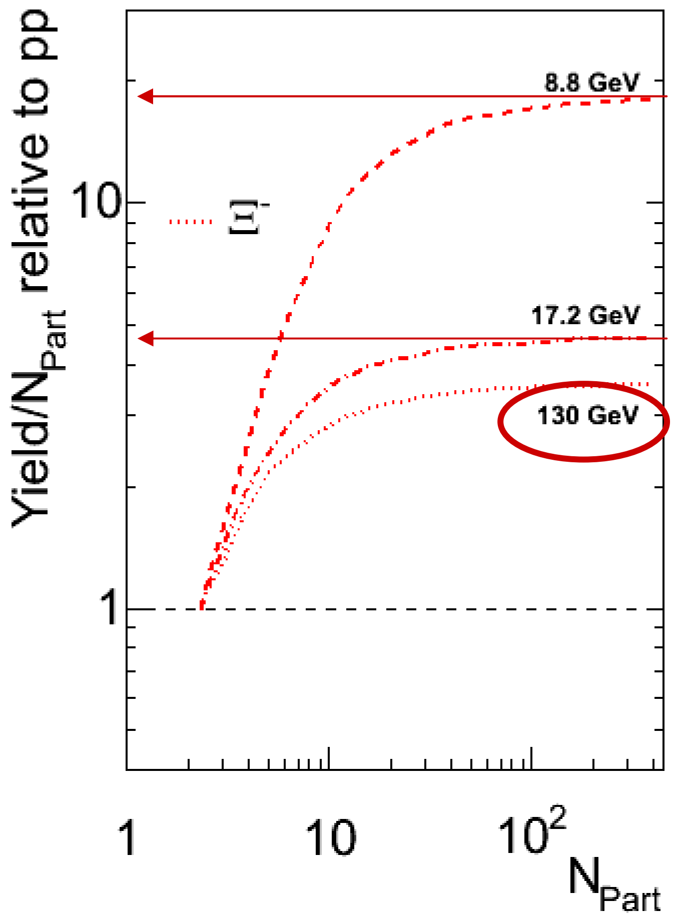


- Similar scaling for baryons and anti-baryons

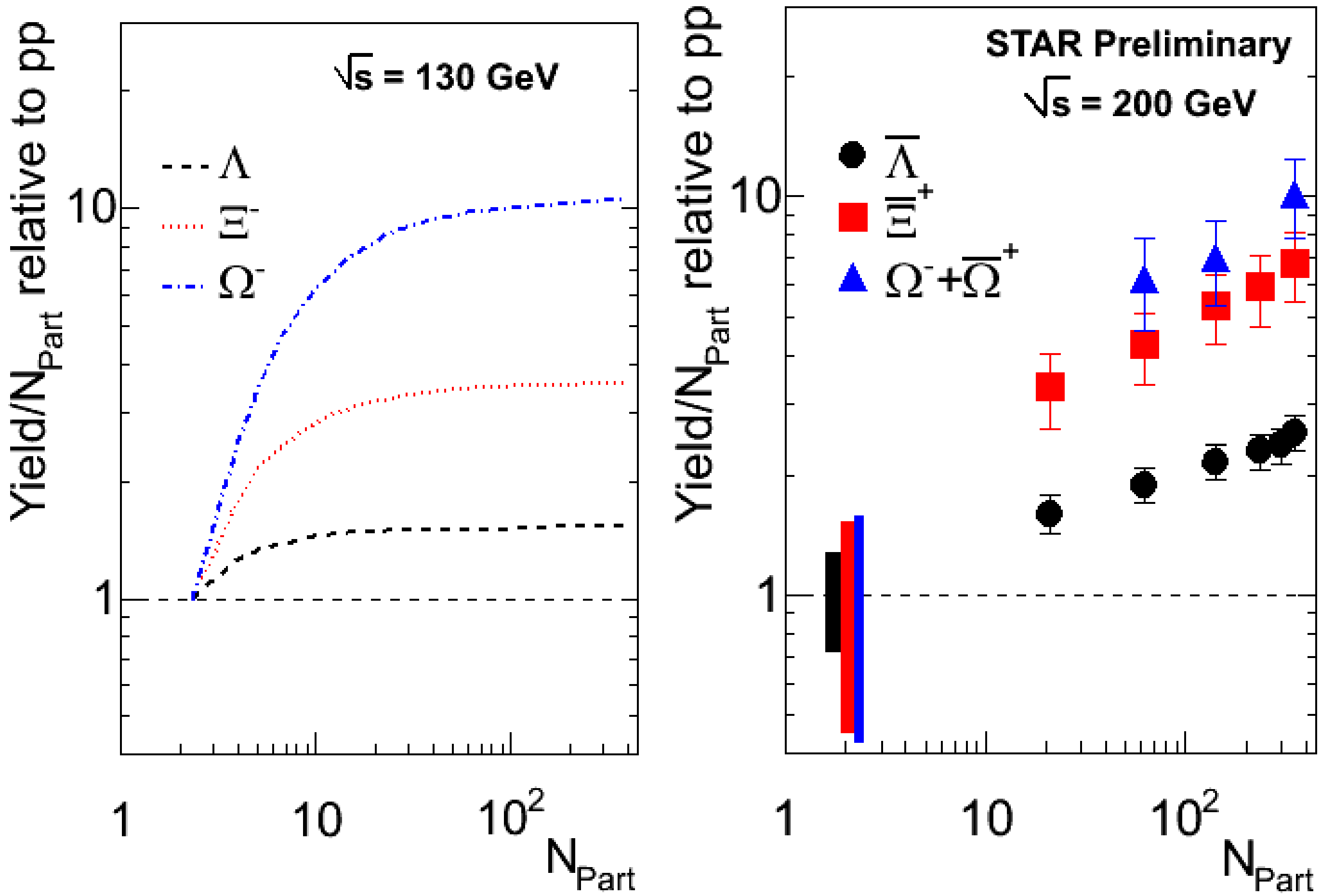
…or Phase space Suppression

[Tounsi & Redlich: hep-ph/0111159]





Phase space suppression smaller at RHIC



- Comparison of a **model @ 130** and **data @ 200 GeV**…
- Correlation volume not well modeled by N_{part}
- ➢ Importance of the scaling (more than the normalization)

Strange Meson Production

Results from BRAHMS and KaOS

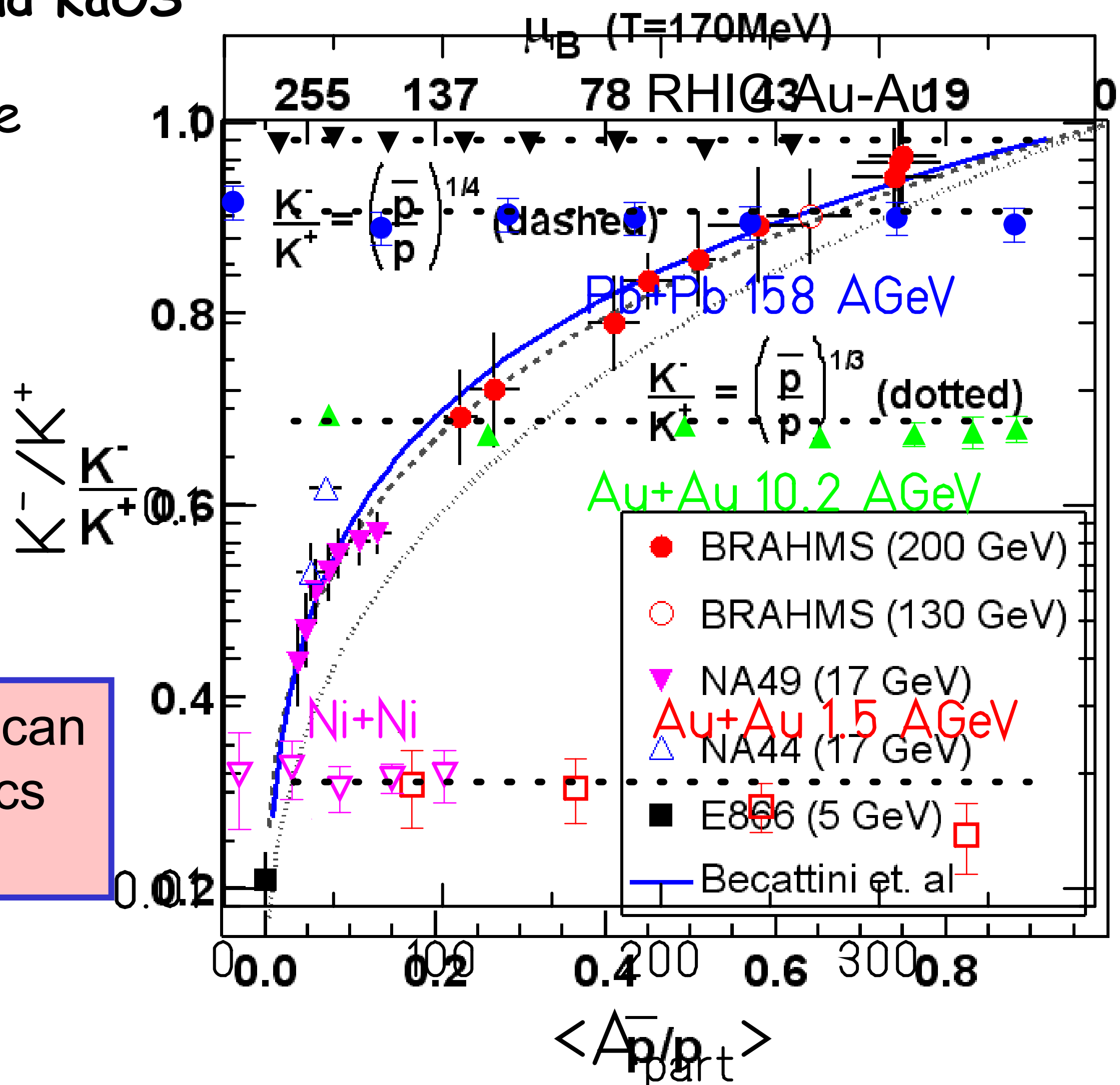
Kaons carry large percentage of strangeness content.

$K^- = \bar{u}s$

$K^+ = \bar{s}u$

Ratio (~ $\bar{u}/u$) shows pair production vs baryon transport.

By varying rapidity range, we can study many different physics regions (mapping μ_B)

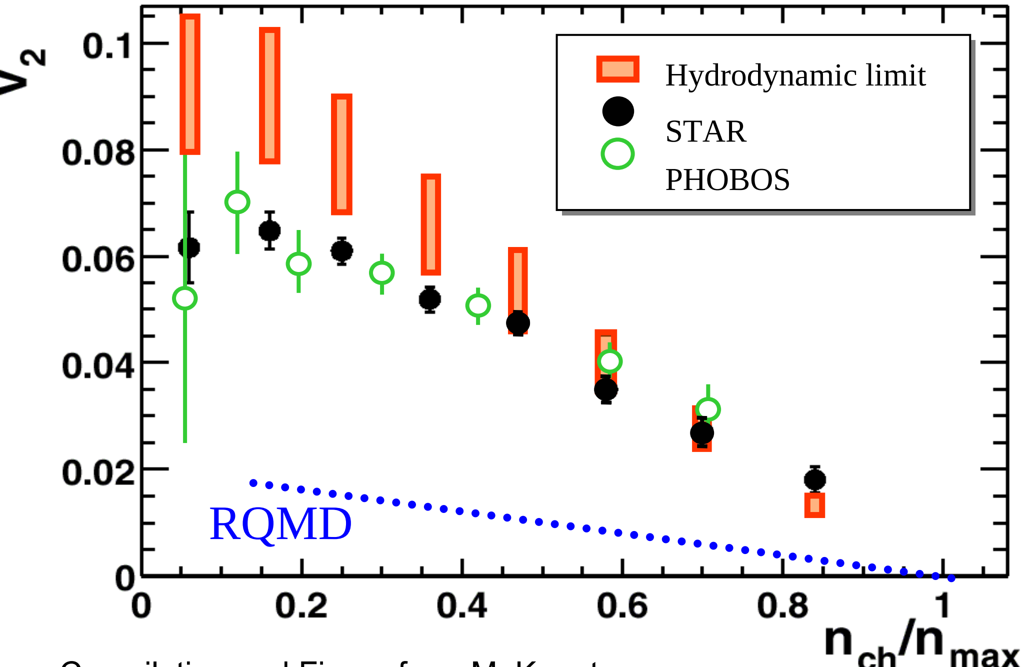


Elliptic flow

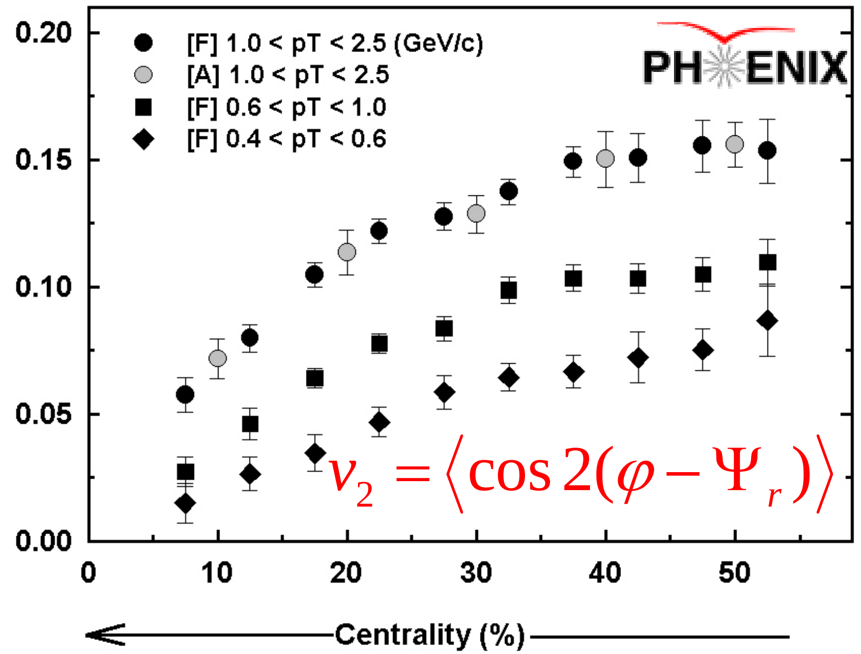
PHOBOS: Phys. Rev. Lett. **89**, 222301 (2002)

STAR: Phys. Rev. Lett. **86**, 402 (2001)

PHENIX: Phys. Rev. Lett. 89, 212301 (2002)



Compilation and Figure from M. Kaneta



First time in Heavy-Ion Collisions a system created which at low p_t is in quantitative agreement with ideal hydrodynamic model predictions for v_2 up to mid-central collisions